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APPLICATION OF GEOPHYSICAL TECHNIQUES IN OIL SANDS

DSS FILE NO. 05SQ.23440-4-9243

SUBMITTED TO: Energy, Mines & Resources Canada
Calgary Coal Research Laboratory

SUBMITTED BY: Terracon Geotechnique Ltd.

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June 27, 1985

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ATTENTION: Mr. George Zahary
Manager, Calgary Coal Research Laboratory (CANMET)

Dear Sir:

Re: **Application of Geophysical Techniques in Oil Sands**
DSS File No. 05SQ.23440-4-9243

We are pleased to submit the attached final report on the Application of Geophysical Techniques in Oil Sands with emphasis on mine highwall stability.

The report documents the work completed as per the scope of work outlined in the above referenced contract. The comments and information requirements resulting from a review of the draft report have been incorporated in the final report.

We appreciate the opportunity of completing this task and will be pleased to discuss any aspects of the study at your convenience.

Yours sincerely,

F.Z. Khan, P.Eng.
Principal

Distribution List:

Mr. G. Zahary, Calgary Coal Research Laboratory (9 copies)
Mr. Eric Fresque, Science and Professional Services Directorate (1 copy)
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EXECUTIVE SUMMARY

This review study has examined the current state-of-the-art of geophysical methods applied to the problem of dragline security in oil sand mines. Information and expertise have been drawn from state-of-the-art sources.

The problem of dragline security stems from the operation of 69 m^3 draglines operating on 50 metre high oil sand benches. These benches have demonstrated that they are prone to highwall failure by a variety of mechanisms or modes. These modes of failure are categorized as; stress relief slabbing; block failure (translation only or translation and rotation); toe bulging; and progressive basal failure. Primarily only one failure mechanism, the block failure, is of significance with respect to dragline security.

The block failure mode offers a significant threat to the mining operation because of certain inherent characteristics. These characteristics include; the tendency of the failures to occur along both old and freshly excavated highwall surfaces and hence in close proximity to the draglines themselves; rapidity of failure; frequency of occurrence; size; and difficulty in prediction.

Block failures are caused by a coincidental combination of geological factors, groundwater conditions and excavation activity. The groundwater conditions are generally similar in the oil sands and generally unfavourable in the sense that the oil sands are fully saturated, poorly drained and usually have a full head condition. Excavation activity including rate of excavation, dragline loading and highwall slope angle are reasonably consistent. Furthermore, block failures are relatively insensitive to the practical highwall angle range of 40 to 55°. However, the geological conditions are quite variable in terms of the primary bedding dip angle, dip direction, joints and the presence

of continuous clay beds. It is the coincidence of these structural geology and stratigraphic factors which trigger the block failures. More specifically, a sequence of sediments containing clay layers with true dips exceeding 8° to 10° "out of" the excavated face is the key triggering mechanism.

Syncrude Canada has developed a simple framework for its remedial approach to evaluating and avoiding potential block failures. This approach includes three steps. These are: first, identify the high risk areas; secondly, continuously monitor highwall performance generally and more intensely in the areas of dragline operation; and thirdly, take corrective action where conditions warrant. The next paragraph elaborates upon these three steps.

The high risk areas are defined by the structural geology conditions and these, in turn, are interpreted from geological face mapping data, core dip measurements and dipmeter logs. The second step of continuously monitoring the performance of the highwall includes the measurement of surface and subsurface movement (shear strains) and the verification of pore water pressure profiles. These measurements are normally conducted with borehole slope indicators and pneumatic piezometers installed in boreholes. The third step involves corrective or remedial action for areas which have been shown to be of unacceptably high risk. This action generally dictates changing the dragline position relative to the cut slope, changing the geometry of the excavation cut as made by the dragline and/or setting additional monitoring sites. Corrective actions to disrupt bedding planes and reduce pore pressures by blasting procedures or by dragline excavation and backfilling of critical areas are also implemented as practical operating procedures.

The structurally complex nature of the oil sands coupled with limited point (one-dimensional) data sources, weakens the geological interpretation of the two-dimensional target structures (sequences of stacked steeply dipping planes composed of interbedded sand and clay layers). Multiple point data to trace and accurately map these structures in three dimensions at reasonable cost is required to provide the required accuracy in the geological interpretation. Syncrude has pursued this goal with surface geophysical field tests at sites with known geology. These tests were conducted with the benefit of general experience gained from a variety of surface and borehole geophysical methods applied to the oil sands. These surface methods have included reflection and refraction seismic, resistivity, electromagnetic and transient electromagnetic. The borehole methods have included sonic, density, resistivity, self-potential, gamma and neutron-porosity.

However, based on the record of success of acoustics in sea bottom profiling, the surface seismic reflection technique was selected. This field testing program at Syncrude utilized a number of conventional energy sources and geophone spreads at selected test sites. The results in terms of specific delineation of dipping bed sequences were unacceptable to Syncrude. A number of factors contributed to the failure of these experiments including sound sources with frequencies and energy levels which were lower than required, poor transducer/ground coupling, high extraneous noise levels, improper signal shielding, insufficient signal processing to eliminate ground roll and air blast, insufficient channel capability, insufficient redundancy and an incomplete testing format. The latter parameter results from a lack of borehole impedance data (density and sonic logs) and vertical profile testing.

Theoretical examination of the available test data in this study has shown that there is a chance of achieving successful test results in a seismic reflection program if a very specific feasibility testing program, with tailored equipment as recommended and discussed herein, is followed. This testing program must first select a test site. Secondly, at this site it is critical to assess the impedance and reflection coefficient values which are typical of the lithologies in the upper oil sands. The normal range of impedance contrasts in deep hydrocarbon seismic exploration is 0.5 to 2.0. For the McMurray Formation lithologies, a reflection coefficient range of 0.01 to 0.3 is estimated based upon available density and seismic velocity data. It is estimated that the reflection coefficients must be at least 0.05 in order to achieve adequate bed identification by seismic reflection techniques. Thirdly, the thickness of the detectable impedance structures will allow an estimate of the frequency necessary for the energy source to be made. Present data indicate a sound source capable of frequencies in the 200 to 500 Hz range is required. Energy levels for appropriate depth penetration (50 m) must be adequate. The field system and data processing systems must be optimized to eliminate problems specific to the oil sands; high noise environments, low impedance differences, high energy absorption, poor transducer coupling conditions, and shallow probing depths.

This method may have be be supplemented by other methods such as E.M. However, no other surface or borehole method on its own merits is recommended "in solo".

With respect to indirect applications, there is a reasonable chance that seismic reflection and electromagnetic methods may be employed in a manner which would delineate those facies which are common to highwall block failures. This information would assist in identifying areas requiring more detailed study. Furthermore, preliminary studies

have shown that a correlation of borehole density data and peak shear strengths may be achievable on a facies basis. However, much more data are required to verify this indirect application.

This report concludes with a review of the basic exploration surface and borehole geophysical methods which are available and which have been applied to the geological and economic evaluation of oil sand leases in the Athabasca area to define other geological targets such as formation boundaries, etc.

RESUME ADMINISTRATIF

Cette étude critique examine ce qu'il ya de meilleur en ce qui concerne les méthodes géophysiques appliquées aux problèmes de securité relatifs aux excavatrices dans les carrières de sables bitumineux. Les informations et l'expertise ont été extraites des meilleures sources.

Les problèmes de sécurité des excavatrices sont ceux relatifs à l'opération d'excavatrices de 69 m^3 qui opèrent sur des bancs de taille de 50 mètres de haut dans les sables bitumineux. Ces bancs ont démontré leur propension à une faillite du front de taille qui est le résultat d'une variété de mécanismes ou de modes. Ces modes de faillite appartiennent à plusieurs catégories qui sont les suivantes: diminution des contraintes par éboulement par blocs; faillite en blocs (avec, ou bien mouvement de translation ou bien encore avec translation et rotation); déformation de la base; et enfin faillite progressive de la base. La faillite en blocs est essentiellement le seul mécanisme qui ait de l'importance en ce qui concerne la sécurité des excavatrices.

Le mode de faillite en blocs présente une menace importante pour les opérations de mine, à cause de certains caractères naturels. Ces caractères incluent: la tendance aux faillites à se produire le long des surfaces de taille, qu'elles soient récentes ou anciennes, et de ce fait proches des excavatrices elles-mêmes; rapidité de la faillite, et fréquence de l'évènement; dimensions et enfin, difficulté de prédiction.

Les faillites en blocs sont le résultat de la combinaison de facteurs géologiques, des conditions hydrogéologiques et des activités d'excavation. Les conditions hydrogéologiques sont en général constantes dans les sables bitumineux, et en général aussi, défavorables dans le sens que les sables bitumineux sont saturés, qu'ils ont un très mauvais drainage et qu'en général les niveaux piézométriques sont

élevés. Les activites d'excavation qui incluent la vitesse d'excavation, les conditions de chargement de l'excavatrice et l'angle du front de taille, sont assez uniformes. Qui plus est, les faillites en blocs sont relativement peu sensibles à un angle du front de taille de 40 à 55°. Cependant, les conditions géologiques elles, sont assez variables en ce qui concerne l'angle de pendage primaire, la direction du pendage, la présence de joints et de lits argileux continus. La présence conjointe de ces facteurs de géologie structurale et des facteurs stratigraphiques crée le mécanisme de déclenchement de ces faillites en blocs. De facon plus spécifique, une séquence de sédiments contenant des lits argileux à pendages vers la face de l'excavation excédant 8 à 10° est le mécanisme clé de déclenchement.

Syncrude Canada a développé un cadre simple aux remèdes à apporter pour évaluer et éviter les faillites en blocs possibles. Cette approche inclut trois étapes, qui sont: en premier lieu l'identification des zones à risque élevé, en second lieu, un contrôle continu de la tenue du front de taille et ceci de facon plus intensive dans les zones ou l'excavation est active et enfin application de mesures correctives lorsque les conditions le demandent. Ce qui suit détaille ces trois étapes.

Les zones à risques élevés sont définies par les conditions de géologie structurale qui sont elles-mêmes obtenues à partir des données geologiques du front de taille, des mesures de pendages sur carottes et des diagraphies de pendimètres. L'étape suivante, dans le contrôle continu de la tenue du front de taille, inclut des mesures des déplacements en surface ainsi qu'en sub-surface (tensions de cisaillement) et vérification des profils de pression de l'eau dans les pores. La troisième étape implique une action curative dans les zones qui montrent des risques élevés. Cette action consiste en general à changer la position de l'excavatrice par rapport à la pente de la taille, le changement de la géometrie de la coupe de l'excavation faite par l'excavatrice, ou bien encore ajout d'autres sites de

contrôle continu. On exécute aussi, comme des procédés courants d'opération, des actions correctives qui consistent à disloquer les plans des couches et à réduire les pressions dans les pores en utilisant les explosifs ou encore par excavation des zones critiques suivie de leur remblaiement.

La nature complexe de la structure des sables bitumineux, couplée à la faible densité des données ponctuelles, limite l'interprétation géologique des structures cibles à deux dimensions (séquences de surfaces empilées à fort pendage, surfaces qui sont composées de couches de sables avec intercalations de bancs d'argiles). Pour délimiter et cartographier de façon précise ces structures dans les trois dimensions à un coût acceptable, et aussi pour fournir la précision requise à l'interprétation géologique, il faut des données multiples. Syncrude a poursuivi ce but, à l'aide d'essais de géophysique de surface, sur le terrain, à des sites où la géologie est déjà connue. Ces essais furent menés en utilisant l'expérience générale acquise dans les méthodes variées de géophysique de surface et en forage, méthodes qui sont appliquées aux sables bitumineux. Ces méthodes de surface incluent la sismique de réfraction et de réflection, résistivité, electromagnétisme et electromagnétisme transitoire. Les méthodes en forage incluent l'utilisation des méthodes soniques, de densité, de résistivité, de potentiel spontané, de porosité gamma et neutron.

Sur la base des succès passés basés sur l'utilisation de l'acoustique pour produire des profils sous-marins, la technique de réflection sismique de surface fut choisie. Durant ce programme d'essais sur le terrain à la mine de Syncrude, un certain nombre de sources d'énergie conventionnelles et des réseaux de géophones furent utilisés à des sites choisis. Les résultats acquis ainsi, en termes de traces spécifiques de séquences de lits inclinés furent jugés inacceptable pour la compagnie Syncrude. Un nombre de facteurs contribuèrent à ce fiasco: sources soniques aux fréquences et aux niveaux d'énergie insuffisants, mauvaises connections du système capteur de pression-

sol, bruits de fonds parasitaires élevés, protection inappropriée du signal, traitement du signal insuffisant pour éliminer le roulement de terrain et les rafales d'air, insuffisance de canaux, compensation insuffisante et enfin un format d'essai incomplet. Le dernier paramètre est le résultat du manque de données sur l'impédance en forage (diagraphies de densité et soniques) et aussi du manque d'essais sur profils verticaux.

Dans cette étude, l'examen théorique des données d'essais disponibles a montré qu'il est possible de parvenir à des résultats d'essais corrects lors d'un programme de sismique de réflection à la condition de suivre un programme très spécifique d'essais de praticabilité, avec un équipement adapté aux conditions locales comme on le recommande et l'explique dans ce qui suit. Ce programme d'essais doit d'abord sélectionner un site d'essais. En second lieu, l'évaluation des valeurs des coefficients d'impédance et de réflection qui sont typiques des lithologies des sables bitumineux supérieurs est tout à fait critique à obtenir au site choisi. La gamme normale des contrastes d'impédance dans l'exploration sismique des hydrocarbures profonds va de 0.5 a 2.0. Dans le cas des lithologies de la Formation Fort McMurray, on estime que la gamme de valeur du coefficient de réflection va de 0.01 a 0.3, cette gamme est basée sur les données de densité et de vitesse sismique. On estime que les coefficients de réflection doivent être au moins égaux à 0.05 pour pouvoir obtenir une identité suffisante des lits à l'aide de techniques de réflection sismique. En dernier lieu, l'épaisseur des structures impédantes détectables, permet d'estimer quelle frequence doit avoir la source d'énergie. Les données actuelles indiquent qu'il faut une source d'onde avec une gamme de fréquence allant de 200 a 500 Herz. Les niveaux d'énergie doivent être suffisants pour obtenir une pénétration adéquate en profondeur (50 m). Le système de terrain et celui de traitement des données doivent être optimalisés pour éliminer dans la mesure du posssible les problèmes qui sont spécifiques aux sables

bitumineux; environnement à bruit de fond de parasites élevé, faibles différences d'impédance, absorption d'énergie élevée, mauvaises conditions de connections des capteurs de pression avec le terrain et faibles profondeurs d'exploration.

Il faudrait ajouter à la methode décrite précédemment, d'autres méthodes telles que l'E.M. Cependant il n'existe pas d'autre méthode qui puisse être recommandée "in solo".

En ce qui concerne les applications indirectes, il est probable que l'on peut employer les méthodes de réflection sismique et magnétiques pour esquisser l'étendue des faciès où les faillites en blocs du front de taille sont fréquentes. Cette information serait très utile pour identifier les zones qui demandent une étude plus détaillee. En outre, des études préliminaires ont montré que l'on peut arriver à mettre en correlation, d'une part, les données de densité en forage, et d'autre part, les forces de cisaillement maxima dans un faciès. Pour pouvoir vérifier cette application, il faudra cependant beaucoup plus de données.

Ce rapport se termine par une revue des méthodes d'exploration de surface de base et aussi des méthodes géophysiques en forage qui sont disponibles et qui ont été appliquées à l'evaluation géologique et économique des concessions de sables bitumineux de la région de l'Athabasca, et à la définition d'autres cibles géologiques telles que les limites de formations etc...

Translated by D. Borneuf.

1.0 INTRODUCTION

1.1 General Statement

This report has been prepared on behalf of the Department of Energy, Mines and Resources of Canada by Terracon Geotechnique Ltd. and Geo-Physi-Con Ltd. under the terms of contract no. 05SQ.23440-4-9243. The study captures the state of development of various shallow geophysical mapping technologies applied to oil sand mining and focusses on their potential for resolving the dragline security problem caused by potential highwall instability.

In assessing the methods and the problems, we have queried those institutions and companies which have undertaken related studies or which have acquired literature on the subject. Case histories have been employed whenever appropriate.

A detailed list of institutions and organizations with an interest in oil sands surface mining and application of geophysical methods is presented in Appendix C.

1.2 Acknowledgements

Terracon and Geo-Physi-Con are pleased to acknowledge the assistance of the research and operating groups of Syncrude Canada Ltd., Gulf Canada Ltd., Esso Resources Ltd., AOSTRA/ARC Oil Sand Information Centre, the University of Calgary and the library facilities of the University of Alberta. The draft report was reviewed by G. Zahary and N. Stuart of the Calgary Coal Research Laboratory, the Scientific Authority for this contract.

Sections 1, 2 and 4 in this report have been prepared by Terracon Geotechnique Ltd. Sections 5, 6, 8 and Appendix B have been prepared by Geo-Physi-Con Co. Ltd. The remaining sections have been prepared jointly.

1.3 Scope and Objectives

The objectives and the range of the investigation in this study include those described in the DSS contract specifications and those which resulted from our discussions with CANMET staff at the initiation of the study. These objectives are:

a) Identify and contact those institutions and Canadian expertise with an interest and experience in geophysical methods and/or oil sands surface mining.
b) Define the problem of dragline security in oil sands mining.
c) Review the state of development of short range geophysical technology and its application or trial test programs in oil sands mining.
d) Obtain and evaluate geophysical field data to select those approaches with the greatest potential of providing information directly applicable to a prediction of stability of a dragline working bench.
e) Review and discuss the potential of geophysical techniques for indirect prediction of geotechnical properties of overburden and oil sands and the importance of these properties to surface mining practice.
f) Identify the knowledge and information gaps and recommendations for further work.

In summary, this study is intended to elucidate the status of geophysical techniques in establishing more cost effective and/or more reliable methods for improving data collection methods necessary for the maintenance of dragline security in oil sand surface mining.

1.4 Technical Approach

The study approach includes a review of the primary information from in-house sources, (Terracon and Geo-Physi-Con) and from oil sand mining operators. Original goals were based upon the contract scope documents and as elucidated in discussions with CANMET staff.

Subsequently, discussions were held with the University of Calgary, geophysical operators previously active in the area and with the primary oil sands operator to review the previous and on-going geophysical programs. Discussions were also held to provide a direction to future studies.

The authors are fully aware of the impact of designing a successful surface geophysical system to evaluate highwall stability in advance of dragline operations. This impact could be measured in two ways. First, as a technical assurance against highwall instability in neutralizing a dragline with consequent oil production losses and secondly, as a more efficient method which would partially supersede current mapping, borehole and monitoring methods.

The essence of the technical investigation examines modes of highwall failure and design methods of ameliorating highwall failures through enhanced data collection by surface geophysical methods.

2.0 GEOLOGY OF THE OIL SANDS AND ITS OVERBURDEN COVER

2.1 General Statement

The geology of the McMurray Formation is discussed in terms of those features which affect highwall stability. These features are primarily structural and stratigraphic characteristics. Some discussion of the genesis of the oil sands is provided in order to better comprehend the geometries, scales and relationships of these characteristics. The geological description includes an overview of the overburden lithostratigraphy (Cretaceous and Pleistocene/Holocene).

The published literature contains a variety of papers which describe the geology of the Athabasca Oil Sands. Those articles which provide the fullest overviews with emphasis on genesis, structure and lithostratigraphy include: Carrigy, 1973; Nelson and Glaister, 1978; Mossop, Kramers, Flach and Rottenfusser, 1979; and Stewart, 1979, (see Section 11.0). Similarly, the equivalent review papers on the overburden geology include those by McPherson and Kathol, 1977 and Isaac, Dusseault, Lobb and Root, 1982, (see Section 11.0).

2.2 McMurray Formation

2.2.1 Major Facies

The oil sands, irrespective of bitumen content, have been subdivided on the basis of environments of deposition into four members. These units reflect early terrestrial deposition (salt-marsh and fluvial), middle deposition (fluvial and estuarine), late deposition (estuarine-marine) and marine. Other interpretations (Carrigy, 1973) which minimize the effect of tidal influence, attribute the middle and upper McMurray sediments to be deposited in very large fluvial regimes or deltaic regimes. In all cases, however, the depositional styles in terms of gross structures and lithologies are generally agreed upon. These sub-units or members of the McMurray Formation consist of the following:

a) Early Terrestrial Deposition: The clastic sediment fill reflects scour fill depositional styles; scour size generally increases progressively upward in the sequence. **The resulting geology is a complex structure with locally steeply dipping beds.**

b) Middle Deposition: Pulses in the marine transgression along with the dynamic nature of deposition has led to repeated channel system scouring, lateral migration and accretion. **The resulting geology is interbedded clay and sand beds with locally steep dips in a common direction.**

c) Late Deposition: The upper McMurray Formation is finer grained, exhibits better lateral bedding continuity and is frequently more bioturbated, reflecting deeper water sedimentation. **The resulting geology is moderately dipping beds with a high clay content which have local and persistent dips over large areas.**

d) Marine Deposition: The upper position of the McMurray Formation and the conformable overlying Clearwater Formation is of marine origin. The resulting geology is a **uniform, near horizontally bedded sequence of shale and soft plastic clay-shales,** with occasional siltstone interbeds.

These facies and their **generalized** relationships are shown in a composite stratigraphic form on Figure 1, Appendix A. These units, from oldest to youngest, are discussed in the following sections together with a brief mention of their geophysical response characteristics and their impact on the design of stable highwalls. The subcrop of the McMurray and other formations in the Athabasca area are illustrated in Figure 2, Appendix A.

2.2.2 Limestone Paleotopographic Surface

The Waterways Formation, composed of carbonates of various origins, is of Devonian age. Stratigraphically, it has been subdivided into five members (Williams et al, 1980). Lithologically, the members are composed of argillites, limey shales, nodular and clastic limestones.

The carbonates are usually micritic or aphanitic and hence quite dense. The Waterways Formation underlies the oil sands and its surface is the principal marker horizon for geological interpretations. This surface has significant control on the lithology and structural configuration of the overlying Cretaceous sediments. Due to the relatively high density contrast (2.4 to 2.9 gms./cc), seismic methods are normally successful in profiling its surface.

The gradient and relief of this surface is of major importance for lithological and structural interpretation of subsequent infill sediments, especially those deposited in the early stages of basin infill. Geophysics may also assist in the determination of post-depositional movement such as karstic-type collapse structures, slumping and graben type faulting and possible sinkhole identification by the degree of concordance of geophysical traces within the Devonian (both seismic density traces and electro-magnetic conductive / non-conductive traces).

Conductive zones within the Devonian consist of pyritic zones, limey argillites and weathered paleosol clays, while non-conductive zones consist of nodular limestone, biohermal and reefal limestone, and fossiliferous micritic zones. Erosional dips on the Devonian surface can be quite steep (in the order of 30°+). Secondary structural features due to faulting and collapse structures such as sinkholes, may exhibit a variety of boundary surfaces with attitudes from shallow to vertical. However, to date there have been no recorded incidents of mining over or across this type of structure.

2.2.3 McMurray Salt-Marsh Fluvial

As seen in Figure 1, Appendix A, this member generally forms the "basal zone" consisting of a variety of lithologies including coarse-sand-conglomerates, silty sands, silty clays and highly plastic "fat" clays. These units are synonymous with the water sand aquifers and the basal clays. Typical distributions, controlled by relief in the

underlying paleotopographic limestone surface, are shown in Figure 3, Appendix A. Water/bitumen contacts are common. Typical densities for the sands range from 2.00 to 2.20 gms/cc. The clays have densities in the order of 2.20 to 2.45 gms/cc. The clays are generally highly conductive; the sands are also highly conductive when water saturated but highly resistive when bitumen saturated. As a consequence, seismic and electrical methods have met with some success in isolating the basal unit.

The lithologies of this unit are involved in deep seated failures in the highwall. These failures are manifested by the development of shear planes in the low strength basal clays and/or heave of the floor at the toe of the highwall as a result of high residual pore pressures in the basal zone. Dips in the basal units are generally less than 5° and do not necessarily promote instability. These failure modes are discussed in more detail in Section 4.3.

2.2.4 McMurray Fluvial-Estuarine

This sequence commonly forms the main oil sand zone. Lithologically, it is composed of fluvial channel sheet sands with cross-bed dips up to 30° and estuarine silts and clays represented by stacked fining upward sequences. Both fluvial and estuarine facies are influenced by tidal effects. The characteristics of both the sands and clay facies are relevant to highwall stability and are discussed below.

The main estuarine sandy facies are as follows:

a) Fluvial Estuarine Facies

Characteristically, these sands are coarse grained, exhibit normal graded bedding and contain large scale cross-beds and the sand sorting is poor to intermediate. Muddy beds of significant lateral continuity (plus 10 metres) are not common due to the high energy scouring nature in which these sands are deposited.

b) Upper Estuarine Facies

These facies are characterized by intermediate to good sand sorting in the medium grain size range. The unit is interbedded with some thick (10 - 20 cm) relatively discontinuous tidal muds. This discontinuous nature is most pronounced towards the channel margin direction. The sands are frequently also interbedded with tidal channel breccias that are composed of upper estuarine sands and generally angular tidal flat and marsh clay clasts that represent channel bank collapse and rip-up clasts resulting from the intensive scouring nature of these sand deposits. The thickness of individual sand beds is commonly 1.0 - 2.5 metres.

c) Lower Estuarine Facies

This unit is characterized by medium and fine grained well sorted sands interbedded on a scale of 0.25 to 1.5 metres thick with thin (0.01 to 0.1 metre thick) tidal muds, and silty tidal flat beds.

The Lower Estuarine sands are characterized by even parallel to low angle cross-beds, which contain abundant current ripple structures and some bioturbation structures, especially in shallow channel segments. Bedding continuity of the tidal mud zones and tidal flat deposits (slack water suspension deposits) is quite pronounced. Individual beds can extend up to 150 metres in either direction from the channel thalweg towards the channel margins and can extend over 1.0 kilometres parallel to the channel axis. Channel stacking, accretion and cross-scouring are noticeably present in this facies type.

The main estuarine silty and muddy facies are as follows:

d) Sandy Tidal Flats and Muddy Tidal Flats

These are composed of thinly interbedded fine sands, silts and muds deposited on the channel margins in conjunction with the tidal channel sands. The Tidal Flat units, which are sub-divided on the

basis of sand-clay content, may be continuously bedded and/or highly bioturbated. These deposits are herein considered as relatively flat lying in nature and of concern because of their overall muddy nature (reject zones) and contact with scour channel sands at relatively steep angles.

e) Estuarine Channel Shoreface

This unit is composed primarily of fine grained material of composition identical to tidal flat. It is finely interbedded clay-silt and minor sand layers which often are strongly bioturbated. The unit is considered to be deposited in the lower estuarine shoreface regime in scour channel trends. Its fine grained nature is attributed to overall calm water conditions combined with its relative distance from the sand source.

The foregoing analysis implies that deep channels may be filled with relatively steeply dipping fine grained, finely interbedded clays, silts and fine sand. These channels are interpreted to be up to 500 metres wide and may have dips of up to 15° on the channel margin areas. Their origin is partly attributed to transgressive pulses (flooding tidal channel scours) and partly to cut-offs from sediment source or other channel pirating effects, both of which create a condition in which a deep channel scour is infilled by fine grained suspension type sediments.

The net result is persistent but erratically occurring steeply dipping beds, some of which are composed of relatively clean "fat" clays. These structures and relationships are illustrated in cross-section format in Figure 4, Appendix A for a one bench mining configuration and Figure 5 for a two bench system. In addition, Figure 6 presents a plan view perspective of these scour channels, while Figure 7 illustrates the features in a detailed block view and "cut-out" perspective.

2.2.5 McMurray Marine

The upper estuarine and marine sediments are generally interbedded at the top of the oil sands sequence. The lithologies are predominantly silty sands. They are thinly but evenly bedded, flat lying and frequently truncate the underlying but steeply dipping estuarine sediments. Thin interbeds of black clays are common.

The spatial and structural relationships, and bed continuity for these lithologies are also presented in Figures 4, 5 and 6 in Appendix A.

These facies do not usually contribute to highwall or bench instability problems.

2.3 Clearwater Formation

The Clearwater Formation is a black clay-shale with minor interbedded siltstones of marine origin. It achieves a maximum thickness of 75 metres and is predominantly flat lying with members being correlatable over several kilometres or more (Figure 8, Appendix A).

The Clearwater sediments can be deeply eroded; consequently, remnant outliers, ice-thrusted and rafted remnants, scarps and disturbed, weathered and sheared zones are common. Stability problems have occurred in this material both in cut slopes as well as a foundation for tailings dykes and waste dumps. These problems are particularly enhanced where the clay shales are in a weathered and sheared state.

2.4 Pleistocene-Holocene Sediments

The entire oil sand area has been glaciated and left with a residue of unconsolidated and uncemented sediments of glacial, fluvial and lacustrine action. These materials and their typical spatial relationships are shown in Figure 8 of Appendix A. Further details on their geology and geotechnical characteristics can be obtained from McPherson et al, 1979 and Isaac et al, 1982. Because of the methods of mining, none

of these materials have played a significant role in highwall stability at the Syncrude mine and hence are not discussed further.

2.5 Structural Geology Features

2.5.1 Bedding

The regional dip of the top of the Wabiskaw Member of the Clearwater Formation varies from 1.3 m/km in a southerly direction (Nelson and Glaister, 1978) to as much as 3° to 5° (52 to 87 m/km) in a southwesterly direction (Fair and Lord, 1983). This regional dip also appears to be related to the direction and orientation of channels of Cretaceous age (McMurray Lithology) of both the fluvial and estuarine facies. **The manifestation of these characteristics is a consistent and common dip direction to the south or southwest for many of the lithologies common to the fluvial and estuarine facies of the McMurray Formation. This structural manifestation,** when combined with clay beds (low shear strength lithologies) and moderate pore pressures **has had the greatest contribution to highwall instability.**

2.5.2 Jointing

The oil sands and related formations contain three orthogonal joint sets which are generally sub-vertical (Khan et al, 1980). These patterns in the Athabasca area are consistent with data gathered on a regional basis (Babcock, 1975). The three orthogonal sets each consist of two joint families at 90° to one another. Two of these joint sets (1 and 3), as shown in Figure 9 of Appendix A extend into the Waterways Limestone Formation (Williams et al, 1980).

The spacing of the joints in the limestone are generally less than 10 metres (Williams et al, 1980). Joint spacings in the oil sand are less reliable but are believed to be approximately the same as in the limestone.

As a consequence of both the orientation and the spacing, these joint patterns have contributed to highwall instability by providing planar boundary surfaces of low tensile and reduced shear strength. This mechanism is discussed in greater detail in Section 3.0.

2.5.3 Stress History

Depth of burial of these sediments has never exceeded 500' (153 m) (Nelson and Glaister, 1978), more than at present. Consequently, for the purposes of shear strength behaviour, the clays in the Clearwater and McMurray Formations can be considered to be moderately overconsolidated.

The horizontal to vertical stress ratio (Ko) in the oil sands has been examined with variable results; theoretically derived values of 5.0 (Brooker & Khan, 1980) and 3.5 (Scott et al, 1985) are reported. However, this stress pattern is not germaine to the block failure mode.

2.6 Summary of Geological Factors Critical to Stable Mine Highwall Design

Those features which are critical to achieving a stable highwall design are well known (Khan et al, 1980, 1982 and Fair et al, 1983, 1984). These features are rigorously reviewed immediately following:

2.6.1 Primary Bedding Dips Coupled with Clay Beds

The occurrence of primary bedding dips out of a mine bench face and coincident with beds of a relatively low shear strength lithology promotes highwall instability. This structural geology setting is common to the aforementioned estuarine facies, which are characteristic of the upper half of the McMurray Formation. The bedding dips range from a few degrees to 30°. The most common lithologies which have these characteristics are the Tidal Channel Muds (see Figure 1 in Appendix A). Tidal Channel Muds (TCM's) are commonly located in the mid-portion of the McMurray Formation and the clay bed thicknesses are generally greater than 10 cm and often reach 30 to 50 cm in thickness. Cross-cutting deeply incised channel structures are common

to these facies. The interbedded sands and clay beds are quite distinctive on mine highwalls with strongly contrasting properties.

The second facies which have relatively steeply dipping beds are the bedded shoreface deposits of estuarine origin, (see the Composite Stratigraphic Column in Figure 1 of Appendix A). Generally these facies are located near the top of the McMurray Formation. Usually the bedding is very thin (a few centimetres) and the discrete bed lithologies do not contrast strongly. That is, they are often sandy-silty-clays with a wide range of grain sizes (i.e. very poorly sorted).

Consequently, the definition of these clay bed units in terms of their location and attitude is vital to predicting the stability behaviour of the slope.

2.6.2 Other Factors

Highwall stability is affected by other geological factors which include joint patterns, pore pressures and shear strengths. However, these factors, because of their common occurrence while contributing to highwall instability, do not control it.

Consequently, geological/geophysical techniques to alleviate slope stability problems should concentrate upon the identification of the geological structure of the primary bedding.

3.0 PHYSICAL PROPERTIES

Geophysical methods utilize differences in physical properties of geologic strata. A summary of the physical properties of materials commonly encountered in surface mineable oil sands deposits is presented in this section.

3.1 In-Situ Density

The density ranges for the major lithologic units of the Fort McMurray area are given in Table 1 on the following page. The major density difference occurs at the McMurray Formation and Devonian interface. In contrast, the density variation between the clay/silt-sand interfaces within the McMurray Formation are relatively small. Since many of the drill holes are cased to the Cretaceous, there is limited borehole geophysical density data on the Holocene and Pleistocene overburden. However, sufficient data are available from ASTM laboratory density measurements on undisturbed samples for these overburden materials. Typical density logs from the Fort McMurray area are shown in Figures 10 and 11. Geophysical methods that exploit contrasts in density include the gravity and seismic methods.

3.2 Electrical Resistivity

The electrical resistivity of earth materials varies from about 0.1 ohm-m to in excess of 10,000 ohm-m. There are a number of factors which determine electrical resistivity of lithologic units in surface mineable oil sands. These dominant factors are clay content, porosity, salinity of pore water, and percent of water and/or bitumen saturation. Some general relations are given in Figures 12 to 17. Figure 12 shows the relation between soil types and resistivity for non-saline pore water. In Figure 13, the general range of electrical resistivity found in the various lithologic units in the Fort McMurray area is presented. It is evident that there is some overlap in the range of electrical resistivities of the lithologic units. Figures 14 and 15 show the relations between bitumen saturation and resistivity for the former and the

TABLE 1

DENSITY RANGE FOR MAJOR LITHOLOGIC UNITS (gm/cc)

Overburden	
Holocene Clay & Sands	1.30 - 1.95
Pleistocene Clay	1.85 - 2.15
Pleistocene Till	2.00 - 2.30
Clearwater Formation	
High Plasticity Clays	1.80 - 2.20
Low Plasticity Clays	2.00 - 2.25
Silty Sands	2.00 - 2.30
Siltstone	2.60 - 3.10
McMurray Formation	
Bituminous Sands	2.00 - 2.20
Clayey Silts & Silty Clays	2.20 - 2.45
Water Sands	2.00 - 2.30
Siltstones/Sandstones	2.50 - 3.00
Devonian Limestone	2.40 - 2.90

relation between bitumen saturation, resistivity and porosity. Typical electrical logs from the surface mineable oil sands area are shown in Figures 10 and 11. Figure 16 shows typical lithological properties and corresponding resistivity response of oil sand cores.

3.3 Seismic Velocity

Elastic waves travel at different velocities in different rocks. Dependent on the type of wave, elastic waves behave in certain ways when encountering interfaces between rocks. The seismic compression wave velocity of the lithologic units in the surface mineable oil sands area varies from about 250 metres/second for unconsolidated Pleistocene materials to 4500 metres/second for competent Devonian limestones. The seismic shear wave velocities of the lithologic units in the surface mineable oil sands area vary from 100 metres/second to 400 metres/second. Table 2 on the following page presents the range of velocities for both compression and shear waves in the study area. It is evident from these data that there are significant seismic velocity contrasts occurring at major geologic boundaries.

3.4 Natural Gamma Ray Emission

Natural gamma radiation is found in all geologic settings. This radiation is a part of the energy released by the nuclei of naturally occurring unstable elements as they decay to a more stable state. In sedimentary environments, the common unstable elements are potassium 40, uranium 238 and thorium 232. The natural gamma ray emmissivity is commonly exploited in borehole geophysical logging. Figure 17 shows a cross plot of log resistivity and gamma ray reflection. The plot assumes that for comparable sand sections, as delineated by the gamma ray curve that have constant bitumen saturation, any change in resistivity on the log is due to a change in the formation water resistivity. The plot is used in conjunction with Figure 14 to determine the appropriate resistivity vs bitumen relationship. Natural gamma ray emmissivity is not commonly exploited in surface geophysics in oil sands since the overburden cover tends to strongly attenuate the natural radiation.

TABLE 2

VELOCITY RANGE FOR MAJOR LITHOLOGIC UNITS

	COMPRESSION VELOCITY (m/s)	SHEAR VELOCITY (m/s)*
Pleistocene (unsaturated)	250 - 800	100 - 200
(saturated)	1800 - 2100	100 - 200
Clearwater Formation	1800 - 2100	280 - 400
McMurray Formation	1800 - 2100	280 - 400
Devonian	3500 - 4500	---

* based on limited data

NOTE: Laboratory tests have reported the following velocity ranges:

McMurray Formation (at room temperature) (Mraz et al)	1650±50 m/s (Compression Velocity) 575±25 m/s (Shear Velocity)
Devonian Limestone (Williams et al)	2970±310 to 5340 m/s (Compression Velocity)

4.0 DRAGLINE SECURITY

4.1 Definition of the Problem

Operation's experience with large draglines at Syncrude Canada Ltd.'s surface oil sand mine has shown that highwall failures have occurred from the inception of mining (see Khan et al, 1980; Brooker and Khan, 1980; Khan et al, 1982; and Fair and Lord, 1983 and 1984). In fact, slope failures occurred in excavations in oil sand which were required for the construction of the extraction plant dump pocket, (Brooker and Khan, 1980). Suncor Ltd. has also had a record of bench failures. None of these slope failures has involved mining equipment at either operation, but several failures at the Syncrude Mine have come close to an operating dragline.

Nevertheless, the loss of a dragline caused by a highwall slope failure would represent a substantial capital replacement cost and even more importantly, a substantial loss of production. Syncrude has experienced approximately 17 block slide failures (Isaac and Lord, 1984) since dragline mining commenced in June of 1977. All failures were instigated by primary clay bedding dips occurring "out of" the excavated highwall face. Contributing factors included low shear strength clays (ϕ' = 12 to 25° approximately) and high pore water pressures.

Other types of failures, i.e. slabbing, toe bulging and progressive basal failures, have also occurred with varying frequency. The various mechanisms of highwall instability encountered in oil sand mining are discussed in Section 4.3.

4.2 Mining Methods

The two methods currently being used to excavate and transport oil sand to extraction plants are the single bench dragline strip operation and the double bench bucketwheel excavator operation. Both methods employ mobile equipment to strip and remove the overburden materials composed of non-indurated and unconsolidated glacial deposits,

clay-shales of the Clearwater Formation and the upper rejects (lean oil sand) of the McMurray Formation. The waste materials are either placed in spoil piles off the mine site proper or placed back into the mined out areas.

The single bench operation used at Syncrude employs four 69 cu. metre (90 cu. yards) draglines operating directly on the oil sand and excavating a full height (approximately 40-50 m) bench in one pass. Each cut panel is approximately 25 metres wide. Various configurations of the dragline tub position relative to the highwall crest are possible. One such configuration is shown in Figure 18 of Appendix A. Various other geometries are given in Khan et al (1980). These configurations are dependent upon the highwall stability conditions. The "maxi-cut" geometry, as shown in Figure 18, is executed in areas where geological structures are unfavourable and potential block failure conditions are known to exist. The maxi-cut geometry allows the dragline to be setback a full cut width from the old highwall (25 metres). This geometry is utilized on the east highwall at the Syncrude mine which is characterized by beds dipping "out of" the highwall. The dragline setback is decreased in areas where stability conditions are favourable, such as the west highwall of the Syncrude mine, where bedding planes generally dip into the highwall face.

The single bench operation, while requiring a relatively high bench, has several distinct mining advantages including:

i) a single pass only is required to extract all oil sand ore,
ii) equipment does not have to operate on a mine floor with poor bearing characteristics,
iii) selective mining is possible with centre rejects being discarded into the mine immediately,
iv) the single bench operation does not necessarily contribute to highwall instability because of its height. **Block failures are independent of highwall height** and relatively insensitive to slope angle.

4.3 Highwall Failure Mechanisms

Operating experience at Syncrude's and, to a lesser extent, Suncor's surface oil sand mines has shown that highwall failures are manifested in several ways. These modes of failure are illustrated in a series of simplified cross-sections in Figure 19 of Appendix A.

The slabbing/toppling failure is a common stress relief phenomenon which does not contribute directly to dragline insecurity. These types of failures are typically associated with highwall angles steeper than 60° and are particularly pronounced in opening box cut conditions.

However, the remainder of the failure classifications do contribute to the dragline security problem. The primary ones include the following classes which are illustrated in Figure 19, Appendix A.

i) Block failure with a single shear plane undergoing translation with or without a rotation component.
ii) Block failure on a single shear plane with a tension crack and having translation movement with or without rotation.
iii) Block failure on a multiple shear plane - translation only.
iv) Block failure bounded by conjugate joint planes - translation only.

Additional mechanisms which involve the entire height of the dragline bench and/or the underlying basal clays include:

v) Highwall toe bulging with crest retrogression,
vi) Progressive basal failure with initial failure at the toe and crest retrogression (also see Figure 20, Appendix A),
vii) Progressive basal failure - multiple block with initiation of the failure at the toe.

While this latter group of failures do adversely affect the dragline operation by causing ore dilution, crest retrogression and minor changes to dragline positioning, they do not pose a serious dragline security problem. Consequently, **this study addresses primarily those failures which affect dragline security - the block failures.**

Current mine operations procedures have emphasized the use of monitoring techniques including visual, slope indicators and surveying methods using electronic distance measuring devices. These monitoring procedures have been supplemented by detailed structural geology mapping by employing several tools including dipmeters, face mapping, and core data. The purpose of this mapping has been to identify potential block slide areas.

Additionally, remedial measures have also been undertaken to ameliorate these potential block slides by blasting or excavation with backfilling and levelling of the operating bench. These methods are discussed more fully in Section 4.5.

4.4 Summary of Key Factors Effecting Highwall Stability with Special Reference to Their Elucidation by Surface Geophysical Methods

Having reviewed the problem of dragline security and the geology of the overburden and the Athabasca oil sands, it would be useful to discuss the key factors responsible for block failures in terms of their potential for delineation by surface geophysical methods.

These factors are:

i) The dip angle and dip direction of the primary bedding planes,
ii) The continuity of the primary beds and the presence of clay beds,
iii) The peak shear strengths of the clays,
iv) The distribution of pore water pressures in the oil sand and clay lithologies,
v) The in-situ bulk density of the materials,
vi) The fracture patterns (joint families) in the oil sand.

4.4.1 Bedding Dips and Bed Continuity

As discussed in Section 2.6, the most important oil sand characteristic to evaluate in order to ensure dragline security against highwall block failure is the primary bedding dip, both magnitude and direction. A

face cut which results in adverse or "out of the wall" bedding dips is the primary (but not the only) triggering mechanism for instigating block failure. Seismic reflection to identify the primary bedding dip and its direction offers the most efficient method for measuring this parameter. This application is discussed in detail in a subsequent section.

Bed continuity over a minimum distance of tens of metres provides a failure block of sufficient size to threaten dragline security. For this parameter, the clay facies which are of concern include offshore mud, offshore silty clay, muddy tidal flat, tidal channel muds, lagoonal muds and pond muds. Their characteristics, including bedding dips and continuity, are summarized in Figure 1 of Appendix A. The reflection seismic method appears to offer the most promise to map these features. This method is discussed in more detail in a subsequent section.

4.4.2 Shear Strengths

In addition to unfavourable dip angles, lithologies with low shear strengths are another common characteristic of block failure zones in oil sand highwalls. The low strength lithologies in the clay beds include (from oldest to youngest facies), pond muds, lagoonal muds, tidal channel clays and offshore lagoonal muds. These facies are clearly illustrated in the Composite Stratigraphic Column shown in Figure 1 of Appendix A. These units are widely distributed in the stratigraphic column but those facies with the steeper dips commonly occur in the top one third of the McMurray Formation.

Shear strength data must be determined directly by field or laboratory test procedures or indirectly by stability back-analysis on actual block failures. However, there is a reasonable possibility that shear strength data may be correlated with geophysical log density data since shear strength is generally recognized as being dependent on density for most clastic materials. Previous study on this correlation (client confidential data) showed some promise.

4.4.3 Pore Pressure Distribution

Geophysics may play a role in determining water table locations and hence pore pressures in the oil sands. However, several properties of the oil sands mitigate this application. These factors are discussed together with a general discussion on the groundwater regime in oil sands in the next two sub-sections.

4.4.3.1 Pore Pressures

For oil sands which have not been disturbed by mining, excavation or dewatering, instrumentation and observation of the pore pressure conditions has shown that the water levels tend to follow a hydrostatic gradient with depth. Generally all of the lithologic units are saturated. Generally the pore pressures can be related to a water table level close to the surface of the McMurray Formation.

In the case of the Clearwater Formation overlying the McMurray Formation, there are no published data but it is likely that the pore pressure profile would be generally continuous between the two formations. Furthermore, the pore pressures in the oil sands are often directly related to the water table in the Pleistocene materials lying on top of the McMurray. Basically then, on a regional basis, the Pleistocene and the Cretaceous Formations can be construed to be a single hydrostratigraphic unit. This conclusion is in agreement with the work done by Hackbarth and Natassa (1979) on the oil sands hydrogeology on a regional basis. However, this hydraulic model, a continuum if you wish, is inappropriate in the local hydrogeology context when the units are disrupted by mining and/or pumping.

Figures 21 and 22 in Appendix A (after Khan et al, 1982) show typical pore pressure profiles in the oil sands. Figure 21 shows the pore water pressure as a function of depth before and after mining. The effects of basal aquifer dewatering are also evident on this figure. Figure 22

illustrates the typical pore pressure regime in the basal aquifer in response to dewatering by deep wells. These figures illustrate quite clearly that pore water pressures in the oil sands (feed zone) are generally only affected by unloading caused by mining and local drainage at the mining face. Because of their low permeability, the pore pressures in the oil sands are generally unaffected by basal aquifer dewatering. Basal aquifer dewatering is completed to enhance basal stability conditions in two ways (Figure 20, Appendix A). This is accomplished by reducing pore pressures in the basal zone and by reducing the piping potential of the basal sands.

4.4.3.2 Water Quality

The water quality of the groundwater contained in the various lithological units in the McMurray Formation is highly variable in terms of the total dissolved solids content. On a regional basis, (Hackbarth and Natassa, 1979), the values range from 5,000 to 10,000 mg/l in the oil sand with values increasing to the west and north from the Mildred Lake-Bitumont area. These values are probably the result of connate (sea) water being flushed by local flows of groundwater from the surface water systems and hence ameliorating the TDS values. Detailed test work (client confidential) to study the distribution of chloride in oil sands on a stratigraphic basis has shown that there is a great variation vertically and spatially. This variability, together with the variability caused by bitumen as shown on resistivity borehole logs leads to the conclusion that there is little promise for the application of geophysics (either neutron or electrical) to delineating groundwater regimes in the oil sands.

4.4.4 Density

The in-situ bulk density property of a material is the weight/unit volume of the material in its natural state. This property can be measured for most geological materials by using standard ASTM field and laboratory procedures.

The main difficulty with the application of these direct tests when applied to oil sands is the expansion which oil sands tend to undergo when confining stresses are relieved such as when cored or when a fresh mining face is excavated and exposed. Stress relief may result in linear strains of 10% taking place in the resulting samples and/or mine bench faces (Dusseault, 1977). These strains are brought about by the overconsolidated nature of the oil sand and the effect of gas exsolving from the contained fluids (both water and bitumen).

Borehole geophysics offers the possibility of determining the in-situ bulk density without sample disturbance and hence expansion. In this method, the density data are collected continuously by a gamma-gamma tool. The logs must be calibrated for the hole conditions i.e. dry or liquid filled, density of drill mud, hole diameter. The calibration procedure is critical and should involve at least three test blocks of known density for the range of interest (1.7 to 2.5 generally), for any given tool. Furthermore, density tools should be calibrated at the beginning and end of each logging program and a portable calibration for checking the tools between drill holes is also normally done. Density values in cored portions of drill holes or where calibration has not been carried out should not be used in geotechnical analyses.

Density values are normally required for the zone of potential failure. Consequently, density logs which have deep penetration from the borehole, such that the drilling disturbance (expansion of the material) is minimized, are preferred.

4.4.5 Fracture Patterns

Joint patterns in the McMurray Formation and exposed Devonian sections has generally shown a preferential NW and NNW trend and secondary ENE and NNE trends. This joint pattern has been postulated to regional basement tectonics or related to Devonian salt collapse structures.

In the McMurray Formation, fracture surfaces can be stained by iron and manganese oxides, indicating the fractures have been opened long before mining excavation. Data by Babcock (1975), suggest that the Devonian Waterways Formation contains an additional north and east orthogonal joint set which is not exhibited in the oil sands.

Joint families occur with sufficient frequency to promote block instability as illustrated in Figure 23 which represents a case example of a failure at the Syncrude mine. They can be assumed to be ubiquitous to the oil sands. Therefore, further research to develop geophysical methods for their delineation is not warranted.

4.5 Remedial Measures for Enhancing Highwall Stability

There are several basic remedial approaches to analyzing and alleviating the highwall stability problem. The first approach is monitoring. This method utilizes instrumentation on both a general and local basis. The monitoring systems include, visual inspection of the bench and highwall in the vicinity of the operating dragline, slope indicator readings and surveying monitoring methods.

The second approach is geological. This method utilizes core data, dipmeter data and geological mapping data to identify areas of steeply dipping clay beds and essentially provide a structural geology model of areas in which block failures have a high potential for occurring. However, in addition to being labor intensive and expensive, this approach relies on interpretation between "point" data sources for the definition of detailed geologic structure.

Once the unstable areas are identified, appropriate measures incorporating excavation design changes and/or dragline positioning changes can be exercised. Alternatively, the structural geology and pore water pressure profile can be disrupted and hence neutralized by blasting and/or excavation followed by backfilling of the upper portion of the bench.

Dragline positioning and setbacks from the highwall crest have an impact on the dragline production rate. As a general rule, the closer the dragline is positioned to the old highwall crest, the higher the production rate. The increased production rate results from an increased digging efficiency and a reduced swing angle. Moreover, with a single bench operation, the complete recovery of feed from deep sections of the mine (approx. 50 m or more) is improved with reduced dragline setbacks. Consequently, dragline security and production efficiency can often be in conflict in dragline cut design and a consideration of both aspects is required for design optimization. Needless to say, security carries a higher emphasis. The "maxi-cut" geometry and its variations which are utilized on the east highwall at the Syncrude Mine is a product of this optimization. It was developed in 1978 to provide "maximum" security and "maximum" production efficiency.

5.0 GEOPHYSICAL IDENTIFICATION OF AREAS PRONE TO HIGHWALL INSTABILITY

5.1 General Statement

The primary mechanisms of highwall instability affecting dragline security are the block failures. Key geologic factors contributing to block failures are itemized in Section 4.0.

Features of the key geologic factors are readily identifiable using borehole geophysical logging methods. The role of surface geophysics is to provide control and continuity to the interpolation of geologic structure between boreholes, and to suggest suitable locations for additional boreholes. The development of surface geophysical techniques for the block failure problem requires considerable further effort.

5.2 Borehole Geophysical Logging

The geophysical methods outlined in Appendix B are typically applied to both borehole and surface geophysical studies. The major advantage to the use of borehole geophysical methods stems from the fact that they yield vertical profiles of the subsurface which often outline signatures that may easily be correlated to lithology on a hole by hole basis. The actual physical properties measured at a specific depth have less importance in this regard. The actual measurements are themselves necessarily averages of the properties of all materials, including pore fluids, within the effective range of penetration of the measurement made. This is similar to the case of surface geophysical measurements, but on a much smaller scale.

For the problem of block failures an effective suite of borehole geophysical logs would include seismic, electrical, and nuclear geophysical measurements. Additionally, caliper measurements of borehole diameter would be required to determine accurate values for physical properties. Details of the many well logging techniques are aptly described in the reference GSC (1974).

5.2.1 Seismic Borehole Logging

Sonic logs measure the net travel time of acoustic (compression wave) energy between a borehole source and receiver. A variety of source-receiver geometries are used. Usually the net travel time is quoted in microseconds per metre, the inverse of velocity. Shear logs similarly measure the net travel time of energy propagated by shear waves (Appendix B).

Anomalously low compression or shear wave velocity generally correlates to the presence of strata with low strength. Knowledge of both the compression and shear velocities and material density allows estimation of the in-situ dynamic elastic moduli, for example; the shear modulus, Young's modulus, Poisson's ratio and the bulk modulus. The identification of the water table is facilitated since an increase in compression wave velocity to at least 1600 m/s occurs with no appreciable change in shear velocity. A combination of both compression and shear velocity borehole logging can then be successfully applied to the problem of block failures.

In support of anticipated surface seismic measurements, borehole velocity profiles would be invaluable to the interpretation of reflection seismic data by allowing a comparison of interval velocity. Also, they would serve to establish the degree of isotropy in seismic wave velocity within layering and, hence, establish confidence in refraction seismic measurements.

5.2.2 Determination of Elastic Constants

A considerable amount of study and investigation has been conducted in deriving the elastic constants from bulk densities, Poisson's ratio, shear and compressional wave velocities (see for example Tixier, 1973 and Kowalski, 1978). These dynamically determined elastic constants include the shear modulus, bulk modulus, bulk compressibility and Young's modulus. The mathematical relationships between these properties and wave propagation parameters are as follows:

$$G = \frac{\rho b}{t_s^2}$$

$$\lambda + 2G = \frac{\rho b}{\Delta t_c^2}$$

$$K = \frac{1}{c_b} = \frac{3\lambda + 2G}{3} = \rho_L \frac{1}{\Delta t_c^2} - \frac{4}{3\Delta t_s^2}$$

$$E = \frac{3(1-2u)}{K}$$

or

$$E = 2G(1 + u)$$

where: G = shear or torsion modulus

ρ_b = bulk density

Δt_s = shear transit time

λ = Lame constant

Δt_c = compressional transit time

K = bulk modulus

C_b = bulk compressibility

E = Young's modulus of elasticity for tension or compression

u = Poisson's ratio

These relationships hold for isotropic, homogeneous and ideally elastic materials. Elastic constants may be derived from stress-strain relationships which are determined in the laboratory. For ideally elastic materials, the static and dynamic constants are the same. However, for soils and rocks this is not the case and the dynamically determined elastic constants are consistently higher than the static constants (King, 1969). The differences are most pronounced at low confining stresses. From the practical standpoint, dynamically determined constants have several advantages since the measurements are made in-situ are representative of the rock (soil mass and the in-situ stress condition). Conversely, the static measurement requires the recovery of an undisturbed core, presumably representative of the formation and the subsequent restoration of the core to the in-situ state.

Elastic data may be used in the analysis of slope stability conditions by utilizing a finite element program to determine shear stress conditions in a highwall (Dusseault, 1977). These results could then be used to determine the most probable locations for failure and subsequent analysis by the more classical block analysis methods.

5.2.3. Electrical Borehole Logging

A variety of electrical logging techniques are available operating on direct current resistivity, induction, induced polarization, and self potential principles. Their use in oil sands development and operations is widespread. Examples of resistivity logs are shown in Figures 10 and 11, Appendix A. Low resistivity measurements correlate to clay rich materials. Dip meter logs are a special form of resistivity log yielding valuable information on the dip magnitude and direction of layering intercepted in a borehole. Self (spontaneous) potential logs measure the natural electric potential associated, for instance, with the geochemistry of shale boundaries. Apart from the obvious value of dip meter logs for the prediction of block failure, resistivity logging in one form or another would be essential to the interpretation of anticipated surface based direct current resistivity and electromagnetic induction measurements.

5.2.4 Nuclear Borehole Logging

As with electric logging, nuclear borehole logging is widespread in oil sands exploration. Methods include measurement of natural radiation (gamma log) and measurement of the effects of emitted gamma ray or neutrons. The gamma-gamma logs, shown in Figures 10 and 11, Appendix A, measure in-situ material bulk density. Neutron logs indicate hydrogen content. Killeen (in GSC, 1974) mentions that gamma, gamma-gamma and neutron logs may be replaced by the "pulsed-neutron" technique, where all three measurements are made during the progression of the pulse transient.

Knowledge of the material density is of essential importance to geotechnical analysis of slope failures. Also the combination of seismic transit time and material density allow calculation of the seismic reflectivity sequence in the subsurface, which is necessary for successful interpretation of surface based reflection seismic measurements.

5.3 Surface Geophysical Methods

The major advantage of surface geophysical methods is that both the lateral and vertical extent of target strata are monitored. However, strata are not encountered directly, as in borehole logging, and surface geophysical methods are thus influenced by the properties of all strata within the exploration range of the measurement array used. The resolution of thin strata is a characteristic problem. So also is the fact that the methods may be transparent to subsurface boundaries at which the contrast in physical properties is slight.

The interpretation of surface geophysical measurements, because of the screening effect of intervening layers, will always benefit from the availability of borehole logs for confirmation and control. It remains to be demonstrated that surface geophysical measurements of sufficient detail required for the highwall block failure problem can be gathered and interpreted to allow interpolation of relevant structure between boreholes. Surface geophysical methods that may be adaptable to this purpose will likely be variants of the general types of method described below. The reflection seismic method is expected to hold the most promise for this purpose.

5.3.1 Seismic Methods

Refraction seismic techniques, with compression (P) or shear (S) waves, are useful in determining an average thickness-velocity structure, generally involving two or three layers, each of which exhibits marked (greater than about 1.5 to 1) increased velocity over the preceeding layer. The properties and thicknesses of thin beds, or groups of distinct

thin beds, are usually beyond resolution. Often density increases are accompanied by greater seismic velocity. Exceptions are coal and permafrost.

For the block failure problem, refraction methods cannot be expected to be useful in determining the dip, orientation and continuity of primary bedding. This is primarily the result of insufficient velocity contrast between the often complex interbeds of clay and sand, especially if these materials are saturated. However, refraction seismic measurements will be required to control static corrections, to allow successful interpretations of high resolution reflection seismic data. Provision can be made to record adequate refraction data at the time of reflection surveying. Use of the refraction method for highwall stability analysis in open pit coal mines is discussed in Section 6.4.

Reflection seismic techniques, usually only with P waves, are useful in determining the location and continuity of reasonably thin layers. For this purpose, an adequate contrast in acoustic impedance (product of seismic velocity and material density) must exist at the boundary between different materials. This contrast is generally referred to as the reflection coefficient, and is equal to $(Z_2-Z_1)/(Z_2+Z_1)$, where Z_1 and Z_2 are the acoustic impedances in materials above and below a subsurface boundary, respectively. The normal range of impedance contrast encountered in hydrocarbon reflection exploration is 0.5 to 2 (Pulsonics, 1984). This is equivalent to a reflection coefficient range of 0 to 0.3. Negative reflection coefficients indicate that the acoustic impedance is smaller in the material beneath a boundary.

With reference to the problem of block failures which are controlled by primary bedding, the reflection coefficient between the interbedded clays and sands of the McMurray Formation is estimated to be in the range of 0.01 to 0.3. Where the seismic velocity in sands or clays is about the same, which may occur if both materials are saturated, the reflection coefficient depends on the difference in density. The

density difference between the sand and clay lithologies of the McMurray Formation is in the range of 0 to 0.45 gms/cc based on the density ranges recorded in Table 1 in Section 3.1. Consequently, in situations where the seismic velocity in the sands and clays are similar, the reflection coefficient in the lower end of the range can be expected (i.e. 0.01 to 0.1). In areas where the velocity in sands and clays are distinctly different, say 1200 m/s for sand and 1800 m/s for clay, then the reflection coefficient exhibits larger values (0.2 to 0.3). It is estimated that a coefficient of at least 0.05 is required to achieve adequate bedding identification by seismic reflection techniques.

The term "reasonably thin" used above describes the fact that the vertical resolution of the reflection seismic method has a practical limit of between one-quarter and one-sixteenth of the seismic wave length at the dominant frequency. Given that the seismic velocity will not appreciably change the frequency, the only way to increase vertical resolution is to increase the frequency content of the seismic energy.

For example, in order to resolve vertical bedding in the order of 0.5 m thickness in materials with a seismic velocity of 1800 m/s, frequencies in excess of 450 hertz would be required, assuming that the limit of resolution is one-eighth the seismic wave length and that a suitable reflection coefficient exists. The usual frequency content of seismic energy deliverable, even for shallow penetration, is in the order of 60 to 200 hertz.

5.3.2 Electrical Methods

Surface based direct current measurements are of two general kinds, vertical soundings and lateral profiling. In vertical soundings, the resistance is measured across two potential probes placed interior to two current probes. The apparent resistivity, at each current probe

separation, is calculated as the product of resistance and a geometric factor appropriate for the array geometry used. A display of the apparent resistivity as a function of array geometry contains information on the general thickness-resistivity layering in the earth.

In lateral profiling, a fixed electrode configuration is moved along the survey line, monitoring the lateral changes in subsurface resistivity. The exploration depth depends primarily on the array geometry. Again, an apparent resistivity is derived from the resistance measurements and plotted against survey station. Results are used to identify areas where significant lateral variation in earth resistivity occur.

Direct current methods are useful for location of resistive strata, since such strata are often an effective barrier to current. The presence of thick, seasonally frozen (resistive) surface materials may preclude the effective use of these methods in winter. The methods are likely best suited for determining lateral and vertical bulk resistivity in strata above bitumen-rich (resistive) McMurray Formation.

Electromagnetic induction methods generally do not require probe contact with the ground and, as resistive layers become relatively transparent, such methods are suitable for winter operations. Two types are common, those using discrete frequencies over a band of frequencies, and those using pulsed excitations (transient methods). In either case, the data consists of a series of vertical soundings along a profile. The depth of investigation for methods relying on discrete frequencies is controlled by either geometric factors of the measurement array for relatively resistive terrain, or skin depth (depth at which a reduction of about 63% in source amplitude occurs). The depth of investigation for transient methods is dependent upon the electrical properties of the subsurface and time.

For the problem of block failures, electrical methods must be able to delineate areas having measurably distinct resistivity that can be correlated to some orientation feature of the primary bedding. The presence of ion-rich groundwater can complicate interpretation by decreasing the resistivity in sands to a level where they are indistinguishable from clays. It is for this reason that surface electrical methods may prove unsuitable for direct detection of features of the primary bedding.

Subsurface interface radar can be considered the electromagnetic analog of reflection seismic profiling. Penetration is limited by skin depth, since operating frequencies are high (usually megahertz). The skin depth decreases as the square root of terrain resistivity, and is usually in the order of a few metres. Penetration is curtailed in the presence of a low resistivity surface layer (small skin depth). Radar techniques could provide information from shallow layers useful for adjusting the interpretation of other, deeper looking, geophysical data.

5.4 .Combined Borehole - Surface Methods

In combined borehole-surface methods, use is made of sources and receivers placed in boreholes and located on the ground surface. These methods primarily measure the transmission properties of the subsurface. It has yet to be demonstrated that the transmission properties could be used to image the primary bedding planes in the McMurray Formation. Only a small degree of success can be anticipated. These can be considered of secondary importance in relation to the methods discussed above.

6.0 REVIEW OF PREVIOUS FIELD STUDIES

6.1 General Statement

No "off the shelf" surface geophysical method has yet been successfully applied to the delineation of primary bedding planes throughout the McMurray Formation. A description of some recent attempts is given below.

6.2 Subsurface Interface Radar

Hillman (1983) undertook radar profiling in two areas at the Syncrude mine. Measurements were performed on pre-stripped mining benches. The survey was preceeded by an electromagnetic induction survey (EM31) to characterize the spatial distribution of resistivity of near surface materials. Frequency of radar operation was 120 megahertz. Skin depth at this frequency and at the resistivity levels measured is in the order of 1 to 2 metres. Hillman reports a maximum penetration of 3.5 metres. Dipping strata at this shallow depth were observed.

6.3 Shallow Reflection Seismic

During the period 1980 to 1983, Caulfield Engineering undertook some pioneering reflection seismic studies at the Syncrude site. The main thrust of these studies was to determine the feasibility for using high resolution reflection seismic techniques to monitor such parameters as the thickness, dip, and continuity of thin clay beds that can have a particular effect on highwall stability, and the presence and continuity of hard bands. References include a series of reports from Caulfield Engineering to Syncrude Canada Ltd.

The task undertaken by Caulfield Engineering can only be described as immense. There are a wide variety of physical factors to be dealt with in such a study. The work did address what is one key to the problem; to generate, transmit and receive acoustic signals of exceptionally high frequency (>100 Hz). The need for high frequency

follows from the requirement for short wave length in order to optimize resolving ability. Apart from frequency considerations. it is apparent that the study did not address the complexity of interfering wave types which are inherent in shallow reflection prospecting. An example of how useful data are separated from interfering wave types is given in Figure 24, which shows a travel time graph generated on the basis of the stratigraphic model shown. The model is comprised of two strata, the upper representing loosely consolidated disturbed materials and till (@ 300 m/s), and the lower representing oil sands (@ 1200 m/s). Interspersed throughout the oil sands are thin clay seams, taken to occur at increments of 5 metre depths for this example. All layers are considered to be horizontal. No density information has been included for this particular example.

The zone between the direct arrival and refracted arrival corresponds to a time window in which reflections can be observed without interference from low velocity air wave and ground roll events. To the left of the refraction line, no seismic events occur. To the right of the direct arrival, an air wave and high amplitude-low velocity ground roll serve to effectively obscure all reflected energy (shown as dashed lines in the figure). The direct and refracted events are linear in time with distance. Reflected events are linear in the square of the time and distance coordinates, and hence appear as hyperbolic curves on the time distance plot. The wide angle line is a reference line corresponding to time distance coordinated to the left of which subsurface reflection angles exceed 45 degrees. Reflected events become asymptotic to the reflection line for subsurface reflection angles greater than 45°. No provision for the definite time duration (period) of each event has been made in the figure. The impact of period is discussed later in this section.

Figure 24 can be used to design a data acquisition geometry. If all data was to be of infinitessimal period and each event could be unambiguously defined on a seismic record, then there would obviously still remain a problem trying to map energy from reflecting surfaces at depths of less than 10 metres. For mapping to depths between 10 and 20 metres, geophones would have to be placed between 10 and 35 metres from the source points. Previous work in the area attempted to map shallow reflections using offsets of 2 to 12 metres on a pre-stripped bench (Caulfield, 1982). This region is basically unusable due to interference from an air wave and ground roll.

For depths to reflectors greater than 10 metres, the time intervals occurring between reflections from subsurface boundaries 5 metres apart are in the order of 7 milliseconds. The period of each individual event then would have to be less than this amount if events are to appear separated in time. With this limit in mind, it is possible to estimate the frequency range required to observe the events separate in time. The optimal frequency will be just the inverse of the period. Therefore, events will not be separable unless recorded frequencies are greater than 150 hertz. When the thickness intervals between reflecting layers are reduced to less than 5 metres, the requirement for even higher frequency increases. Attempts to consistently generate and measure seismic energy at predominant frequencies greater than 150 hertz will require very special source, receiver and recording equipment. This is discussed further in Section 7.3.1.

For very shallow reflecting boundaries in the 5 to 10 metre depth range, the situation becomes more complex since events corresponding to these boundaries become asymptotic to the refracted arrivals at short offset distances. The period of the refraction needs to be less than 2 milliseconds to unambiguously separate it from the reflection occurring at 5 metres below the refracting surface. Frequencies required will

then be in the order of 500 hertz. Attempts to work at very short offsets will be defeated because of the quick onset of interfering air wave and ground roll energy.

If, for each of the subsurface reflecting horizons noted, we assign the definite thickness of 10 cm, the net difference in two way travel time between the top and bottom of seams will be in the order of 0.2 milliseconds. This is a very short period of time rivaling the sample interval for most modern seismographs.

In order to achieve reflections of suitable strength from boundaries characterized by very slight reflection coefficients, a large redundancy in data is required. It follows then that the data should be recorded according to standard formats so that the large amount of existing processing software, as brought to bear on more traditional reflection seismic data, can be utilized. The preferred methods of processing data are discussed in Section 7.3.1.

6.4 Related Studies at Coal Mines

Highwall instability can occur in prairie coal mines. A key factor affecting instability is the presence of disturbed sediments. These may be identified on the basis of anomalously low shear wave seismic velocity, resulting in high ratios of compression wave to shear wave velocity. Cross borehole shear and compression wave measurements are used to confirm the general velocity-thickness structure identified from surface refraction measurements (ARC, 1985).

7.0 SELECTION OF OPTIMAL GEOPHYSICAL METHODS WITH APPLICATION TO HIGHWALL STABILITY IN THE McMURRAY FORMATION

7.1 General Statement

There is a definite need to develop surface geophysical capability to the stage where detailed geologic structure in oil sands can be monitored between boreholes, so that the potential for block failures can be accurately defined. Standard surface geophysical methodology has yet to be successfully applied for this purpose. It is anticipated that no single type of surface measurement can be developed to meet the necessarily detailed requirements in every case. Instead a combination of complimentary techniques, including borehole geophysical measurements, may be required.

An appropriate procedure of attack for this problem would require a detailed and interdisciplinary study of existing information. This information would be used to establish the suitability of any of a group of geophysical methods. A concise statement of the mapping objectives to be met by geophysical measurements would be formulated at this time. Detailed modelling of the expected geophysical response, based on computer simulation, would then be required to determine if data appropriate to satisfy the mapping objectives could be gathered. Field trials should be undertaken only after these other steps have been addressed.

The critical aspects to be studied for such development are outlined below. Variants of surface geophysical methods, which appear to have the potential for delineating features of the primary bedding, are discussed.

7.2 Feasibility Studies

A feasibility study must include an appreciation of geologic and geotechnical setting, theoretical geophysical limitation, and measurement limitations imposed by available technology. An understanding of the first two items will provide guidelines for which the effectiveness of present or new technology can be assessed, or along which new mapping approaches can be developed.

Feasibility studies will necessarily include a detailed review of geotechnical, geological, and borehole geophysical information. The review will outline the major subsurface parameters to be addressed by geophysical mapping methods. The review should be carried out by a multi-disciplinary team, as assembled for this study.

The theoretical response can be generated for any surface or combined borehole-surface method, based on the perceived detailed subsurface physical model. The theoretical response can be used to determine the expected success of a proposed series of measurements to meet the mapping objectives, to identify optimal field data acquisition geometries, and to indicate suitability of proposed methods of analysis and interpretation.

The study should be based on hard data gathered at a representative site. This site should remain available for field testing and comparison of proposed methods. It would be beneficial if the site was located in a relatively inactive mining area in order to reduce background noise levels.

7.3 Suggested Geophysical Methods

Suggested methods for further study include primarily the reflection seismic method and, to a lesser extent, electrical methods. Field studies would be recommended only after the feasibility of obtaining data suitable for resolution of detailed objectives can be demonstrated.

Tables 3A and 3B, on the following pages, provide a summary of the seismic and electrical methods, their applications, depth range and potential for success in mapping primary bedding in the oil sands. The tables show that the seismic and electrical methods differ in the applicable range of depth. Accordingly, a combined application of seismic and electrical methods may provide the maximum information. Other geophysical methods do not warrant further considerations.

Tables 3A and 3B do not contain a resolution yardstick. It is not possible in the current study to estimate the resolution for the various methods. This is due in part to the number of parameters which impact on each geophysical method. These parameters include the nature and state of overlying and underlying materials, the magnitude of contrast in physical properties at the boundaries of interest, depth of occurrence and the availability of geologic control.

7.3.1 Seismic Reflection Method

As indicated, high resolution shallow reflection seismic profiling appears to have the potential for mapping of significant features related to primary bedding planes in the McMurray Formation. Further development requires improvements in data acquisition, processing and interpretation.

For data acquisition, three points are important. These are: frequency content of data, the strength of reflected signals, and recognition of interfering wave types. The frequency content of data can be expected to be increased using a source rich in high frequency. From the data processing point of view, it would be better if the source frequency content was relatively constant over a broad band of frequencies, rather than a narrow band that is concentrated at high frequency. Geophones capable of producing output voltages that increase with frequency are also desirable. Additionally, the dynamic (energy) range of sampling and recording equipment must have a minimum range of 60 to 100 decibels at a high sample rate to effectively capture the high frequency signals transmitted. Engineering seismographs typically used for this type of work generally have a dynamic range of about one half this amount.

TABLE 3A

SUMMARY OF APPLICABLE SEISMIC METHODS

PRIMARY TECHNIQUE	SECONDARY TECHNIQUE	APPLICATION	DEPTH RANGE	POTENTIAL
Reflection	--	Primary Bedding Dip & Strike	>10 m	Fair to Good
--	Refraction	Static Correction in Support of Reflection	0 to 50 m	Good
--	Crosshole	Identify Low Velocity Zones	Any Depth	Good
--	Sonic/Density Logs	Define Acoustic Impedance/ Reflection Coefficients	Any Depth	Good
--	Vertical Seismic Profiling	Supplement to Reflection Seismic. Provides Velocity Distribution with Depth	Any Depth	Good
Imaging Techniques (Borehole to Borehole and Borehole to Surface)	Imaging Techniques	3 Dimensional Spatial Distribution of Strata	Any Depth	Fair

TABLE 3B

SUMMARY OF APPLICABLE ELECTRICAL METHODS

PRIMARY TECHNIQUE	SECONDARY TECHNIQUE	APPLICATION	DEPTH RANGE	POTENTIAL
Radar	--	Primary Bedding Dip & Strike	0 to 3 m	Poor
--	EM and DC Soundings	Surface Resistivity Measurements to Assess Feasibility of Radar Applications	0 to 20 m	Good
Imaging Technique (Borehole to Borehole and Borehole to Surface)	Imaging Technique	3 Dimensional Spatial Distribution of Strata	Any Depth	Fair
Direct Current Profiling	--	Delineation of Near Surface Dipping Clay Beds	0 to 10 m	Poor to Fair

The strength of reflected signals can be expected to be small realizing the low values of the reflection coefficient at target boundaries. It is anticipated that the signal to noise ratio can be increased by recording data which contains at least a six fold redundancy in coverage at a subsurface boundary.

The problem of interfering wave types can be approached jointly during data acquisition and data processing. From the acquisition standpoint, it can be arranged to record reflected events before interfering wave types using the time-window approach. In processing, velocity dependent interference may be removed using velocity filtering techniques, none of which has yet been applied to data of this type.

From the processing point of view, similar research studies applied to coal mines indicates that the most suitable method for highlighting high frequency data involves statistical wavelet enhancement techniques. For this purpose, a dephasing operator (optimal wavelet) is derived from the field recorded data. The operator is then convolved with the field data and band pass filtered to abstract data with as high frequency content as possible. Data are then statistically corrected, stacked and F-K (frequency-wave number) filtered to eradicate remnant low velocity interference. The form of the operator depends critically on the frequency spectrum of raw data. The approach is best applied to data for which the signal level decrease with increasing frequency is gradual rather than sharp. The requirement of a broad band source, frequency sensitive geophones and a wide dynamic range for recordings would aid this approach to data processing.

Interpretation involves the recognition of reflection patterns in terms of geologic significance and translation of the resulting time section into a depth correct geologic profile. Usually this is accomplished

by comparison with time section synthetically derived from borehole sonic and density logs. The ability to produce a synthetic section based on borehole logging is a strong tool which can also be used to estimate suitable frequency bands over which data should be acquired.

7.3.2 Other Suggested Methods

Direct current profiling and soundings methods may be affected by the overall high resistivity of bitumen-rich McMurray Formation present at the surface of pre-stripped mining benches. Profiling methods may be used to determine the location and strike of steeply dipping clay seams in the shallow subsurface under favourable conditions. Detailed analysis based on a realistic subsurface model will be required to demonstrate the feasibility of surface based electrical measurements to provide information on significant features of primary bedding. It is likely that surface electrical measurements will not be of great value by themselves but will supply some information that can be incorporated into interpretations of reflection seismic data.

Radar techniques show some promise for delineation of bedding structure in the very shallow subsurface (<3 metres). Such information may be usefully incorporated into the interpretation of deeper looking geophysical measurements.

7.4 Indirect Applications

Indirect applications refers to those geophysical techniques which may be correlated to geological or geotechnical parameters that are normally required to evaluate highwall stability. These have been referred to and discussed in various sections of this report and are included here for ease of reference.

There has been some attempt to correlate borehole density log data for clays and silty clays to peak shear strengths. Generally low shear strength or high plastic "fat" clays are characterized by lower than average densities. Consequently, borehole density logs may be used

in a qualitative sense to identify weak horizons and hence potentially unstable areas of the highwall. These exercises have shown some promise. At present, such an application is qualitative at best and it is unlikely that it can be considered as a substitute for laboratory shear strength data. However, with a sufficient data population, a quantitative correlation between laboratory peak shear strength and geophysical signal from borehole logs may be possible. Further study of this aspect is recommended.

The general delineation of facies that are common to highwall block failures (e.g. the Lower Estuarine and Estuarine Shoreface), combined with a definition of the regional bedding dips, may be possible with a combination of surface geophysics electromagnetic and seismic data together with reference borehole data. This information would assist in identifying areas requiring more detailed study.

Finally, the delineation of groundwater and fracture data by induced geophysical methods (correlations) do not show promise of success and are not recommended for further study.

8.0 OTHER APPLICATIONS OF SURFACE GEOPHYSICAL METHODS

8.1 General Statement

In the past, most surface mineable oil sands lease evaluations have been based upon the results of boreholes and the accompanying geologic interpretation of the changes in subsurface conditions between boreholes. The continuity of strata or the delineation of features of limited lateral extent cannot always be recorded from the low density of drilling typical for exploration programs.

Surface geophysical methods have been used to augment costly exploration by drilling. In addition to providing information on the lateral continuity or discontinuity of mappable features, these methods are suitable for locating boreholes in the optimum locations.

8.2 Seismic Methods

Seismic methods are employed to exploit contrasts in seismic velocity and density at boundaries between different lithologic units as described in Sections 2.0 and 3.0. In exploration programs for resource evaluation, refraction seismic methods are commonly used to map the location of the water table and the Devonian. The compressional seismic wave velocity in unconsolidated materials is largely related to the degree of saturation. Above the water table, soils generally exhibit velocities in the order of 800 metres per second (m/s). Beneath the water table, sediments exhibit velocities of between 800 m/s and 2100 m/s. This velocity is essentially that characteristic of water. The Clearwater and McMurray Formations beneath the water table do not have a velocity observably different from that of the saturated soils based on refraction seismic data. At the competent Devonian limestone surface, velocities of between 3500 m/s and 4500 m/s are observed. The large velocity contrast at this interface facilitates accurate placement of the boundary. Figure 25 presents a hypothetical geophysical section from the surface mineable oil sands area. The figure illustrates the ability of refraction seismic methods to map a highly irregular Devonian surface.

Reflection seismic methods have been tested to determine if they can be used to locate the Devonian surface and the presence of reflecting horizons within the McMurray Formation. Figure 26 shows a sample of data that has recently been obtained for this purpose.

8.3 Electrical Methods

Electrical methods used to date exploit resistivity contrasts occurring at the boundaries between the geologic units of different lithology, saturation grade, etc. Two electrical techniques are currently used on a routine basis. They are fixed frequency method (EM) and the transient electromagnetic method (TEM).

The EM method is employed to map the thickness and type of Pleistocene overburden, presence or absence of Clearwater Formation and to locate glacial channels. Under favourable conditions, the method can also be used to map the top of high grade feed or reject zones in the McMurray Formation.

It has been shown (Section 3.0) that soils and rocks of different types can be differentiated by their resistivity. Thus, the magnitude of measured EM signal would change along the survey line according to variations in overburden type and thickness.

The conductive Clearwater Formation is normally characterized by resistivity values which are much lower than those of the Holocene and Pleistocene overburden. As a result, independent EM measurements to different exploration depths would unambiguously indicate the presence or absence of the Clearwater sediments and, in the former case, would map the depth to the Clearwater Formation. When overburden is directly underlain by bitumen saturated McMurray Formation, resistivity increases with depth. If the top of the bitumen rich zone occurs within the upper 25 m, it can often be mapped by the EM technique.

The information on shallow resistivity distribution provided by the EM method is of great support to the TEM data interpretation.

The transient electromagnetic method is invariably used in exploration programs for resource evaluation. The method is employed to delineate bitumen rich and bitumen lean intervals within the McMurray Formation, major changes in bitumen saturation, the presence or absence of the McMurray basal zone, and resistivity variations below the Devonian surface.

It has been shown (Appendix B) that the resistivity of the McMurray Formation increases as its bitumen saturation increases. Thus, the resistivities and thicknesses interpreted from TEM data would provide direct information on bitumen distribution in the subsurface.

The accuracy of all geophysical techniques described depends heavily upon the complexity of the section under investigation. For example, if the McMurray Formation, with high bitumen content, overlies the competent Devonian limestones there is no resistivity contrast at the contact, and electrical techniques can not detect this boundary. Similar situations would occur if the conductive basal zone overlies conductive Devonian limestone. The use of surface geophysical techniques of a non-electrical nature are employed to map the Devonian surface. In the routinely used combination of techniques refraction seismic resolves this problem.

9.0 RECOMMENDED PROGRAM FOR RESEARCH AND DEVELOPMENT

9.1 General Statement

The preceeding discussions indicate that the reflection seismic method has perhaps the best potential for useful application to the problem of monitoring features of the primary bedding within the McMurray Formation.

At this stage, it is felt that the useful application of the method needs to be fully investigated, so that criteria are developed to judge future proposals relying on variants of the method that cannot be put forward at this time. For example, currently available impedance and reflection coefficient data appear to be marginal at best.

9.2 Program for Research and Development

The essential studies required to further the development of reflection seismic methods, and to enhance their usefulness for determining primary bedding detail, are described below. These relate to improvements to data acquisition, processing and interpretation.

A preliminary study would investigate the seismic response of a typical test area. This area should remain available for future field studies. Borehole sonic and density data (impedance values and reflection coefficients) would be incorporated into the derivation of a synthetic seismogram. For this purpose, a borehole compensated sonic log with a resolution equivalent to bedding thicknesses of the test site is recommended. This seismogram would be viewed over a range of frequences to determine which frequencies (expected to be in the order of 300+Hz) are required to capture maximum subsurface detail. Additionally, a study is required to determine the pattern of interpreting events (wave forms). The results of these exercises would help identify acquisition geometries (source-receiver arrays) and confirm the necessary technical specifications of source and recording equipment (i.e. energy levels, frequencies, etc.).

A review of available source, sensor and recording instrumentation can be instituted once the feasibility is established. Additionally, a study of suitable processing and interpretive techniques would be required to ensure that the required data can be recorded and can be reduced to meaningful form.

Once acquisition and processing standards are determined, field tests will be required to supply test data. Field tests should be designed not only to record reflection data, but also to obtain as much refraction data as possible. This will prove important to static correction of reflection data. Additionally, the amplitude and phase attenuation characteristics of the subsurface should be quantified at this stage.

The processing of test data will reveal the effectiveness of the design, high frequency content and increased signal to noise ratio. The ultimate test of the information will be to compare the structural geology interpreted from the reflection seismic data against the geological model derived from independent measurements of dip meter data, face mapping data, trenching data, and oriented core, etc.

10.0 CONCLUSIONS

The major dragline security problem results from the threat of unannounced block failures occurring in the oil sand operating highwall bench. Block failures can and have occurred in a sudden manner with little advance warning and such failures have included in-situ oil sands materials in close proximity to the tub and shoes of operating draglines.

A number of factors contribute to this failure mode. These factors have been shown to be the coincidence of adverse bedding dips ("out-of-the-face" dips), of interbedded oil sand and clay beds; the continuity of the clay beds; jointing; and a moderate to high pore pressure profile.

In order to reduce the frequency of occurrence of the block failures and their impact on mining operations, a mining approach which invokes identification of critical structural geology areas, highwall stability performance monitoring and remedial dragline excavation cut designs, has been implemented. The identification of critical structural geology areas has been derived from point (i.e. borehole) data sources and face mapping data. These geological interpretations could be significantly strengthened by calling upon multiple point data sources such as that offered by geophysical profiling.

The primary failure mechanism affecting dragline security is the block failure. The key geological factors that contribute to the block failure mechanism and that are expected to be mappable geophysically are the orientation, dip and continuity of primary bedding planes and the presence of clayey layers.

Borehole geophysical logging techniques including sonic, density, resistivity and dip meter logs, are capable of identifying prominent features of the primary bedding patterns. The need for surface geophysical technique results from the desire to obtain relevant data that can be used to constrain the interpolation of detailed subsurface structure between boreholes. None of the standard surface based geophysical techniques has yet been shown to be suitable for this purpose.

Surface geophysical techniques have been used in a complimentary fashion in support of exploration. The methods generally lack the resolution required to investigate the primary bedding patterns. The lack of resolution results from screening effects of overlying materials and the fact that little contrast exists in the physical properties between interbedded sands and clays. It can be expected that surface and borehole-surface geophysical techniques will be useful when integrated into a comprehensive exploration program involving relevant geological and geotechnical observation and borehole geophysical logging.

Perhaps the primary surface geophysical method that can be brought to bear on the problem of delineating major features of the bedding planes is high resolution reflection seismic profiling. Supporting sonic and density borehole logs will be acquired. Required development includes the need to generate and record data of much higher frequency (>200 Hz) than has yet been accomplished. Analytical and interpretive procedures must also be improved.

The use of surface based electrical methods can be considered for simplified mapping objectives. Combined borehole-surface, uphole, downhole and crosshole techniques can be envisioned using either seismic or electrical geophysical measurements. Analysis would be basically statistical in nature. Comprehensive interpretive routines are not in place for these types of investigation.

Radar profiling techniques can be applied to monitor layering in the very shallow subsurface. There is little hope of extending the depth range of penetrations. Information of shallow layering could be of consequence to the interpretation of geophysical data encompassing greater penetrations.

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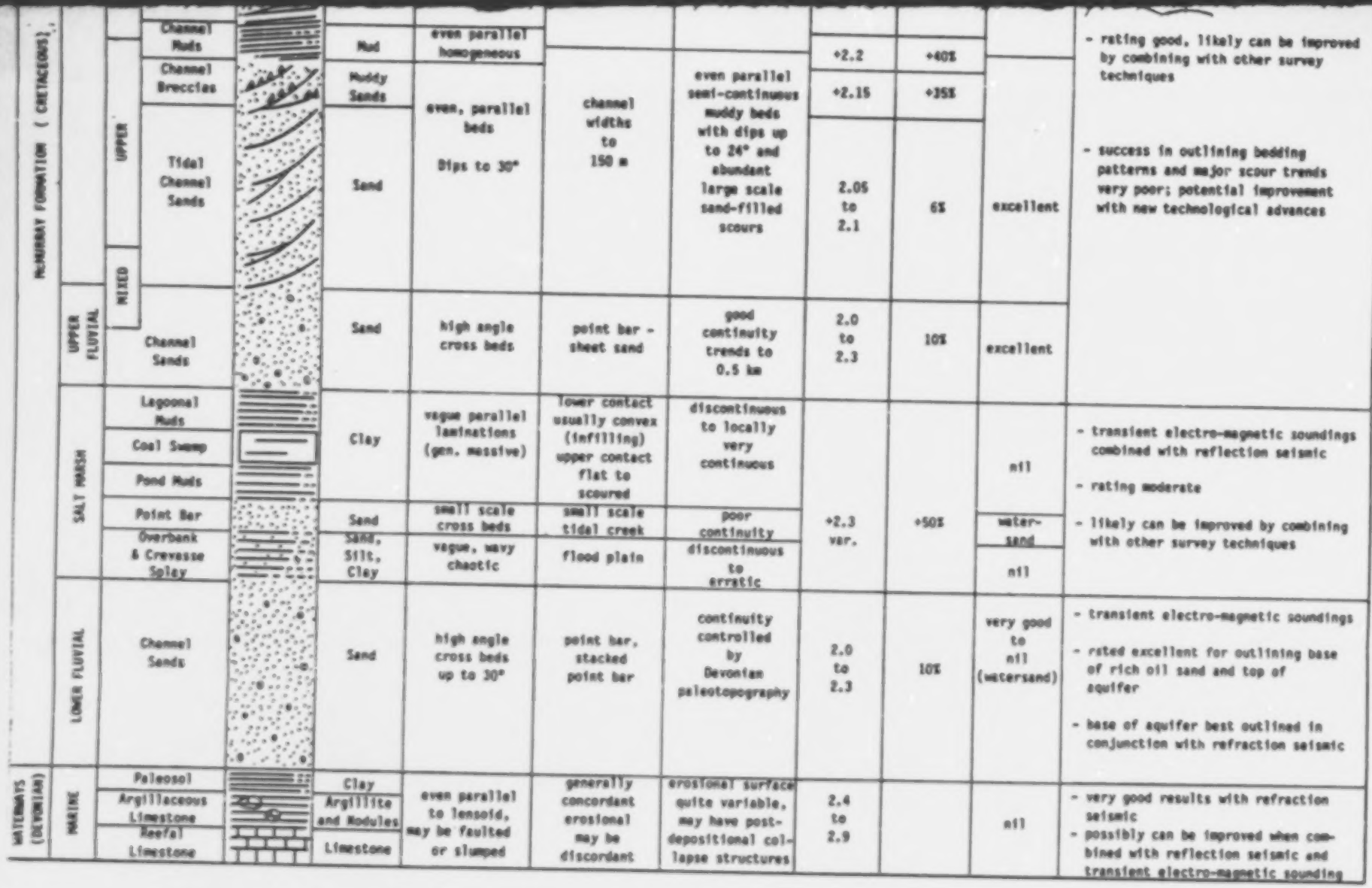
APPENDIX A

FIGURES 1 TO 26

FORMATION AGE	DEPOSITIONAL ENVIRONMENT	FACIES TYPE	LITHOLOGY	SEDIMENTARY STRUCTURES	FORM AND GEOMETRY	BED CONTINUITY AND DIP MAGNITUDE	TYPICAL DENSITY (gm/cc)	TYPICAL FINES (<44μ)	RESERVOIR QUALITY	GENERAL COMMENTS ON SURFACE GEOPHYSICAL METHODS
RECENT		Organic	Muskeg		Recent - topographic control		1.3			- fixed frequency electro-magnetic induction combined with refraction seismic
		Fluvial	Silt							
		Lacustrine	Clay							
PLEISTOCENE	GLACIAL	Fluvial	Sand and Gravel	variable gradation	channel, glacial outwash	very good continuity locally	2.25			- rating good; excellent for outlining Pleistocene buried channels
		Lacustrine	Clay	laminated; varved; massive	water-laid channel, lake	locally continuous	2.0			
		Ice Contact	Assorted (Till)		pred. basal deposited	locally continuous	2.2 var.			
CLEARWATER Fm. (CRETACEOUS)	MARINE	Offshore	Clay, Silty Clay, Minor Fine Sand	even parallel laminae, low density clays, burrowing	pred. thick clayshales interbedded with thin indurated zones and minor glauconitic sand	continuous; conformable at base, glacially eroded at upper surface, dips ≤ 3°	2.1 to 2.7	+50%		- fixed frequency electro-magnetic induction combined with refraction seismic - rating fair, improvement possible if combined with transient electro-magnetic soundings
		Offshore Mud	Clay	even parallel beds	flat	locally continuous	2.3			
		Beach	Sand	homogeneous	flat	locally continuous	2.1	20%	very good	- transient electro-magnetic soundings
		Shoreface	Sand, Silt, Clay	burrowing, wavy parallel, non-parallel, lenticular beds	sometimes channelled, widths up to 500 m	even parallel semi-continuous frequently burrowed Dips to 15°	+2.3	+40%	marginal to poor	- moderate results in thick oil sands
		Shoreface						40%		- no existing suitable geophysical survey techniques for outlining bedding patterns, scour trends and thin aquifer zones, clay zones and oil sand zones
		Muddy Tidal Flat	Silty Clay	even parallel, and burrowing	relatively flat, often scoured into	good continuity		+35%	very poor	
CRETACEOUS)	ESTUARINE	LOWER Sandy Tidal Flat	Sand, Silt, Clay	even parallel, wavy, current laminations, burrowing	channel widths to 300 m	even parallel semi-continuous muddy interbeds with broad low angle sand-filled scours, muddy beds dip to 17°	2.2 to 2.25	+25%	poor to marginal	
		Tidal Channel Sands	Sand	current laminations (e.g. small scale cross bed), ripples			2.05 to 2.1	17%	good	- rich feed grade oil sand best outlined by transient electro-magnetic soundings - rating good, likely can be improved by combining with other survey techniques
		Channel Muds	Mud	even parallel homogeneous			+2.2	+40%		
		Channel Breccias	Muddy Sands	even, parallel	channel widths	even parallel semi-continuous muddy beds	+2.15	+35%		



MCMURRAY FORMATION (CRETACEOUS)	UPPER FLUVIAL	UPPER	Channel Muds		Mud	even parallel homogeneous					- rating good, likely can be improved by combining with other survey techniques
			Channel Breccias		Muddy Sands				+2.2	+40%	
			Tidal Channel Sands		Sand	even, parallel beds Dips to 30°	channel widths to 150 m	even parallel semi-continuous muddy beds with dips up to 24° and abundant large scale sand-filled scours	+2.15 2.05 to 2.1	+35% 6%	excellent - success in outlining bedding patterns and major scour trends very poor; potential improvement with new technological advances
		MIXED									
			Channel Sands		Sand	high angle cross beds	point bar - sheet sand	good continuity trends to 0.5 km	2.0 to 2.3	10%	excellent
	SALT MARSH		Lagoonal Muds		Clay	vague parallel laminations (gen. massive)	lower contact usually convex (infilling) upper contact flat to scoured	discontinuous to locally very continuous	+2.3 var.	+50%	nil - transient electro-magnetic soundings combined with reflection seismic - rating moderate - likely can be improved by combining with other survey techniques
			Coal Swamp								
			Pond Muds								
			Point Bar		Sand	small scale cross beds	small scale tidal creek	poor continuity			water-sand
			Overbank & Crevasse Splay		Sand, Silt, Clay	vague, wavy chaotic	flood plain	discontinuous to erratic			nil
	LOWER FLUVIAL		Channel Sands		Sand	high angle cross beds up to 30°	point bar, stacked point bar	continuity controlled by Devonian paleotopography	2.0 to 2.3	10%	very good to nil (watersand) - transient electro-magnetic soundings - rated excellent for outlining base of rich oil sand and top of aquifer - base of aquifer best outlined in conjunction with refraction seismic
WATERWAYS (DEVONIAN)	MARINE		Paleosol		Clay	even parallel to lensoid, may be faulted or slumped	generally concordant erosional may be discordant	erosional surface quite variable, may have post-depositional collapse structures	2.4 to 2.9		nil - very good results with refraction seismic - possibly can be improved when combined with reflection seismic and transient electro-magnetic sounding
			Argillaceous Limestone		Argillite and Nodules						
			Reefal Limestone		Limestone						

FIGURE 1 : COMPOSITE STRATIGRAPHIC COLUMN OF ATHABASCA OIL SAND AREA WITH APPLICABLE SURFACE GEOPHYSICAL METHODS

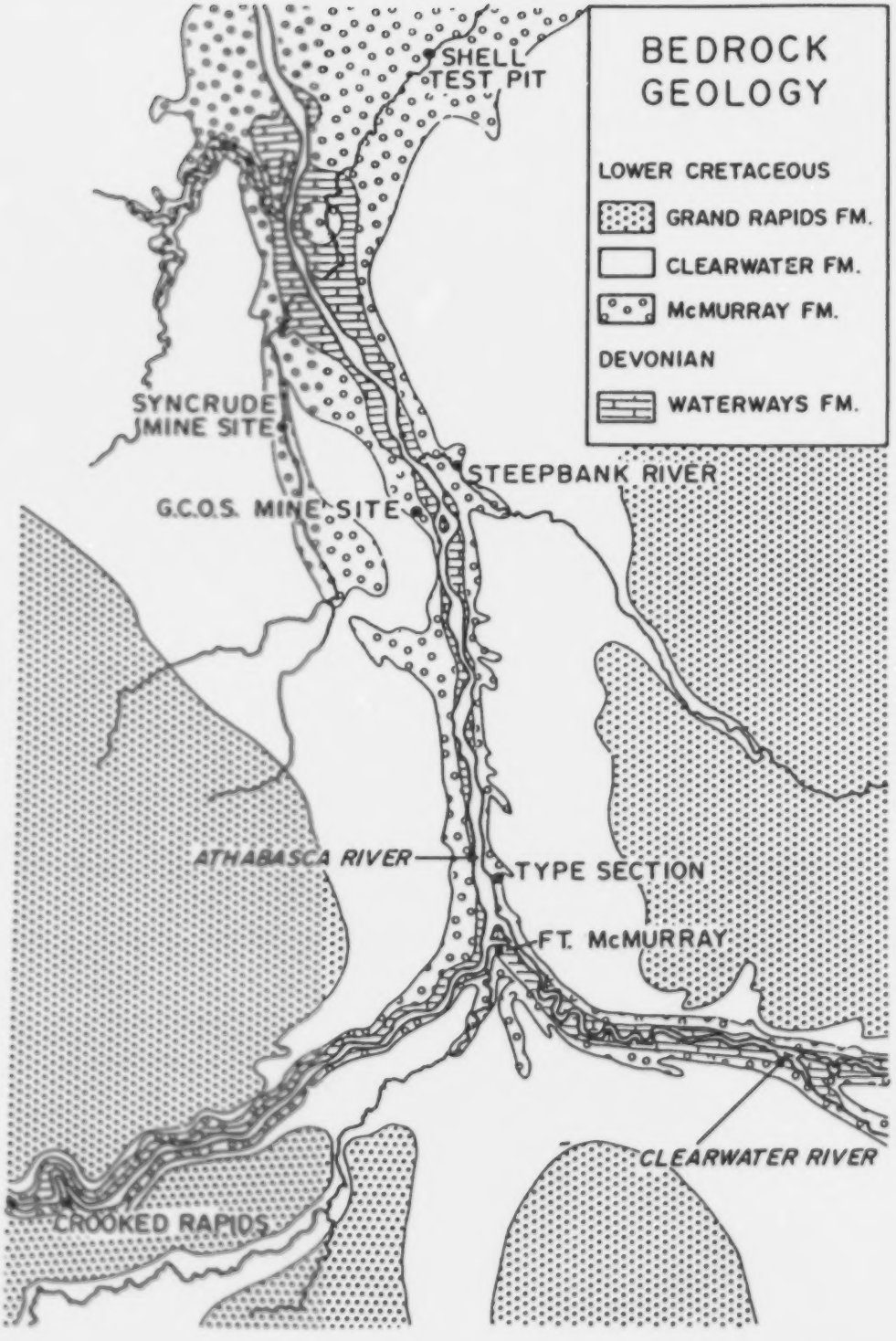


FIGURE 2: BEDROCK GEOLOGY OF THE ATHABASCA OIL SANDS AREA
(after Stewart, 1982)

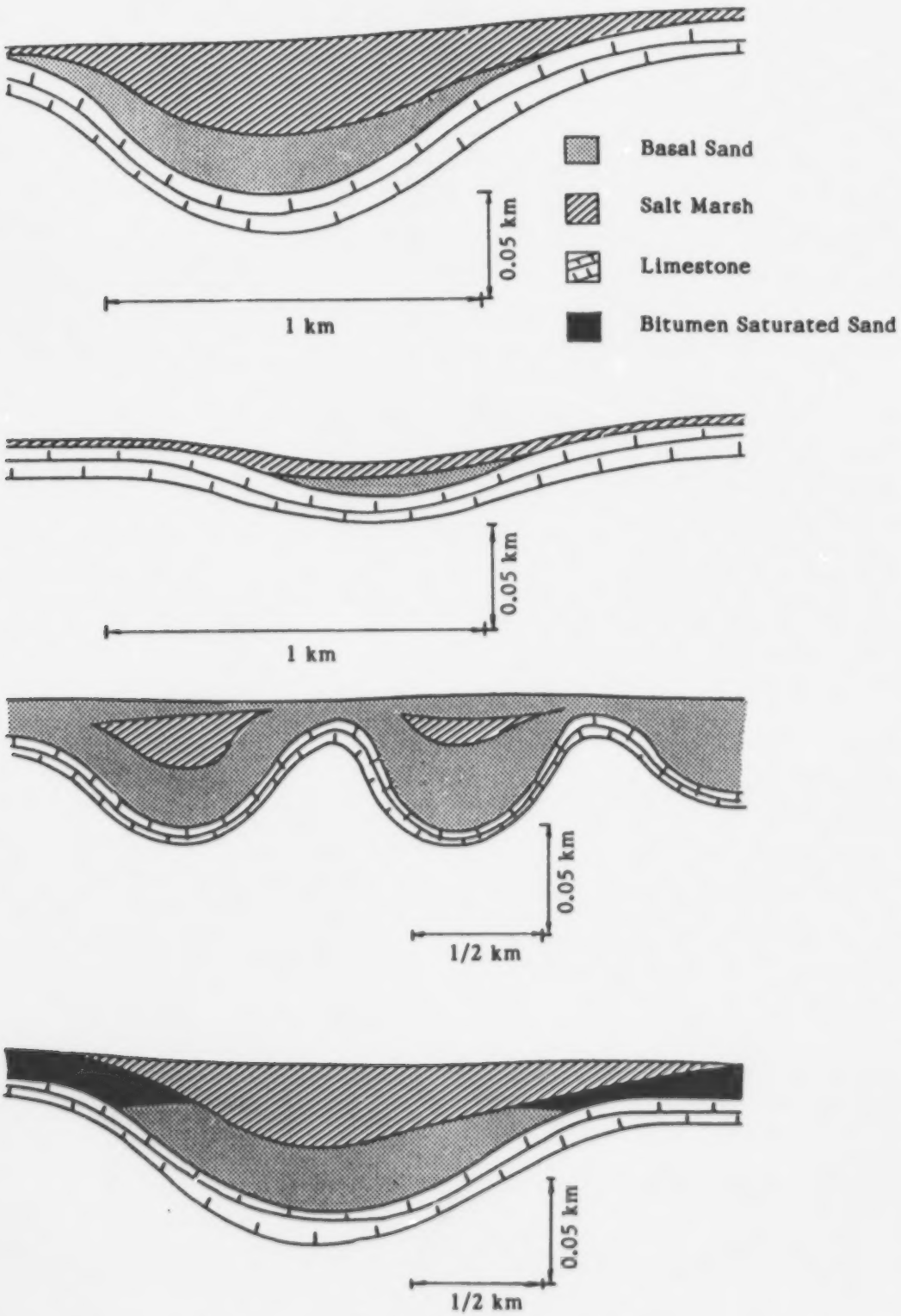


FIGURE 3 : McMURRAY BASAL ZONE ILLUSTRATING THE TYPICAL SPATIAL DISTRIBUTIONS OF THE FACIES, STRUCTURAL DIPS AND RELATION TO THE DEVONIAN PALEOSURFACE

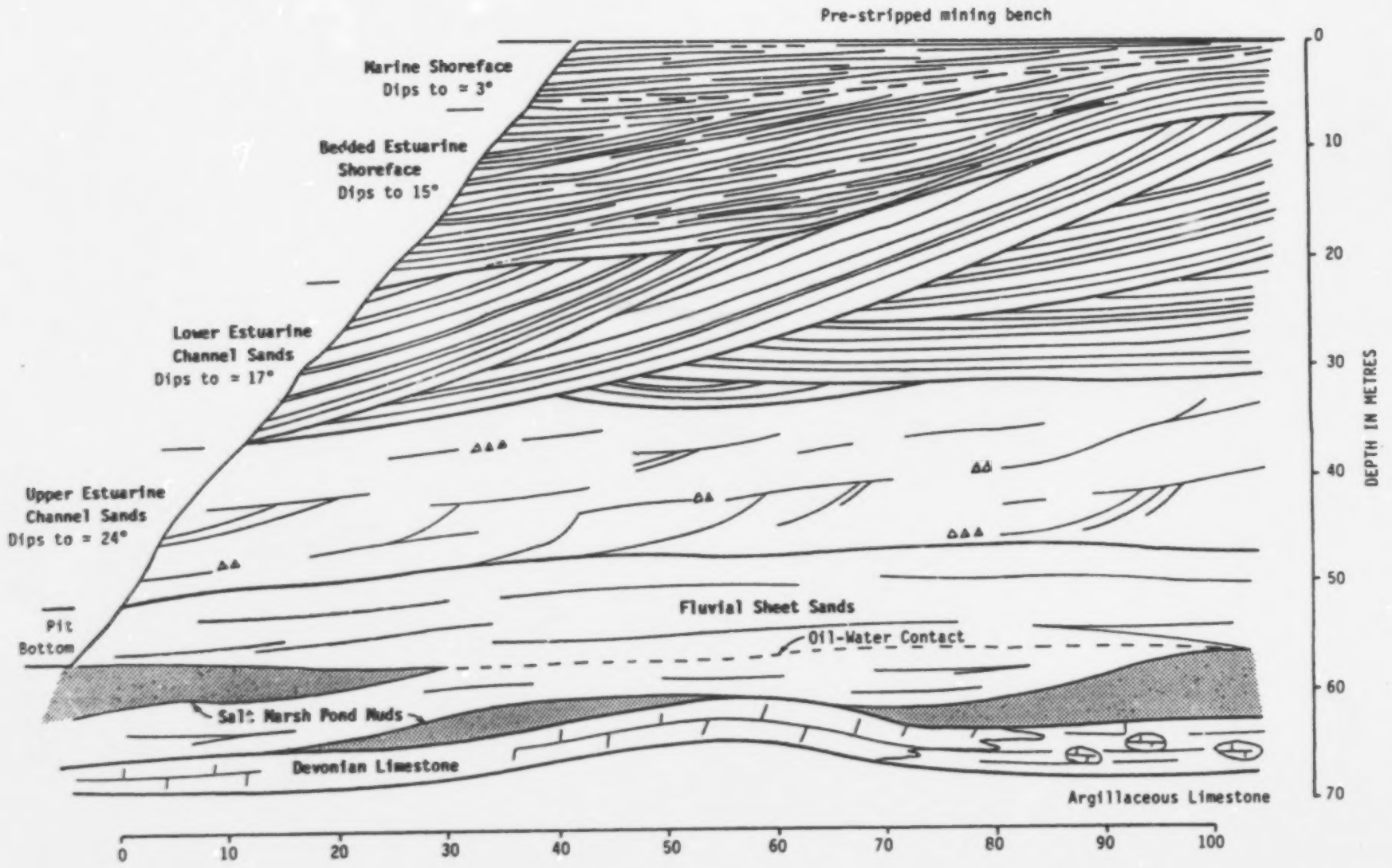
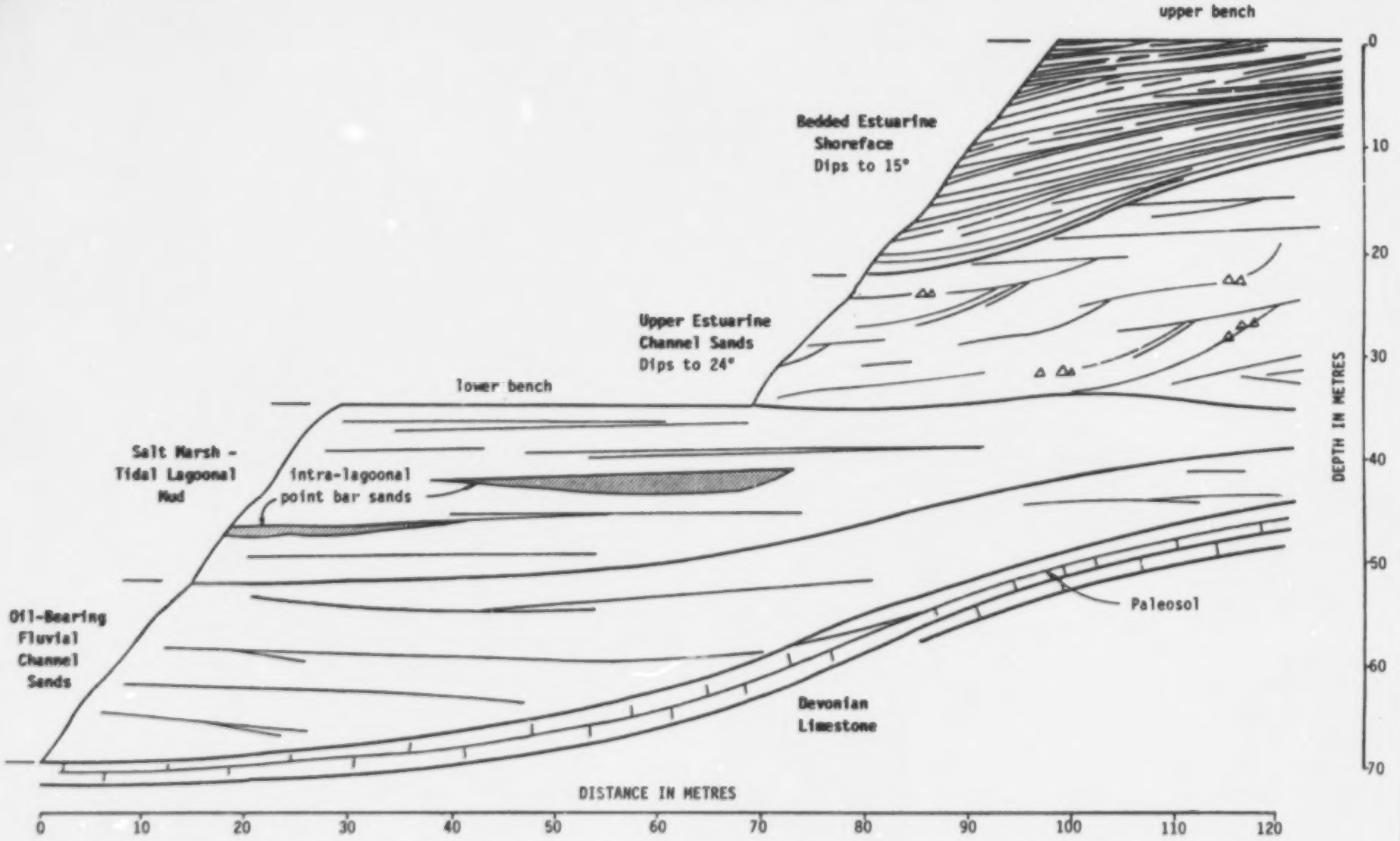


FIGURE 4 : HIGHWALL CROSS-SECTION ILLUSTRATING TYPICAL DEPOSITIONAL ENVIRONMENTS AND ASSOCIATED BEDDING PATTERNS



LEGEND

ΔΔ - breccia
— - facies contact
— - bedding
Scale 1:500

FIGURE 5 : TWO BENCH MINING SYSTEM CROSS-SECTION ILLUSTRATING TYPICAL DEPOSITIONAL ENVIRONMENTS AND ASSOCIATED BEDDING PATTERNS

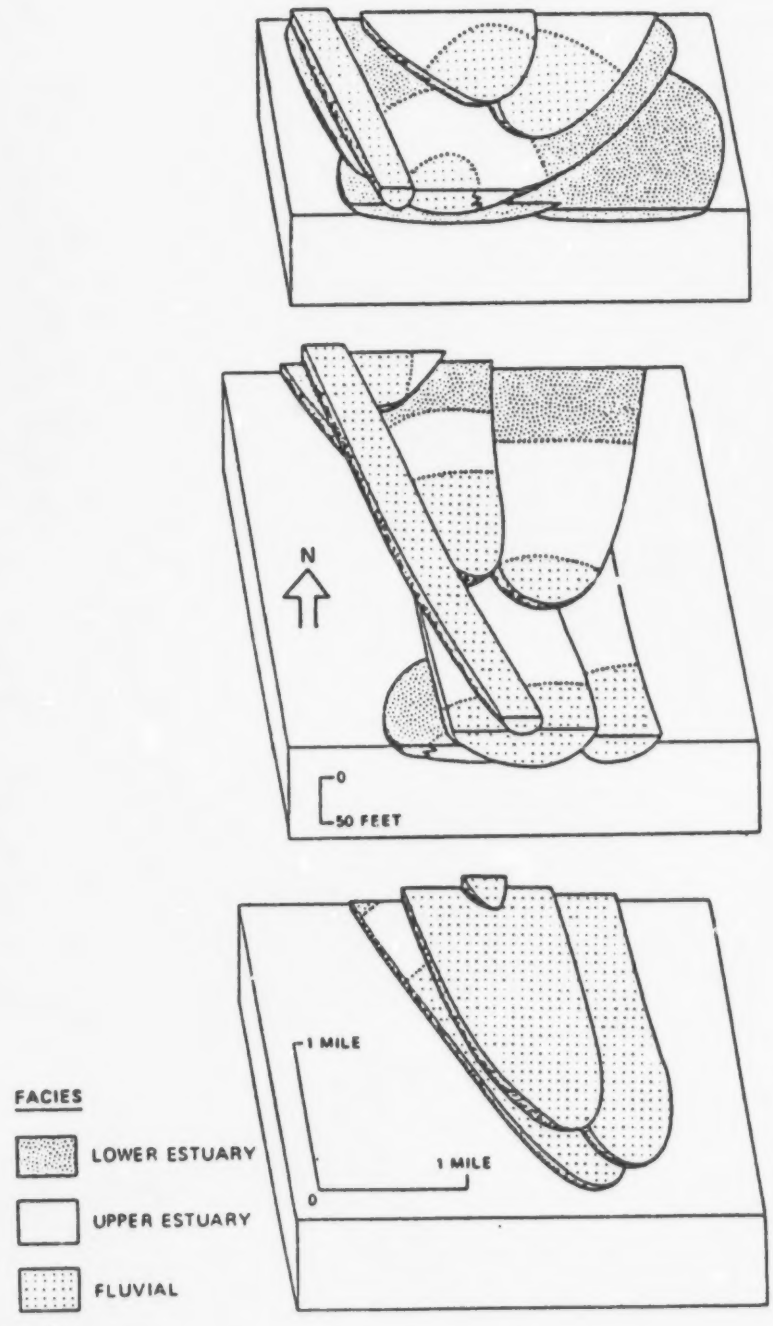


FIGURE 6 : SPATIAL RELATIONSHIPS AND FACIES DISTRIBUTIONS WITHIN A COMPLEX OF ESTUARINE SANDSTONES SANDSTONE BODIES ARE ENCLOSED IN TIDAL-FLAT AND SEAWARD-EQUIVALENT DEPOSITS (after Campbell & Oaks Jr., 1972)

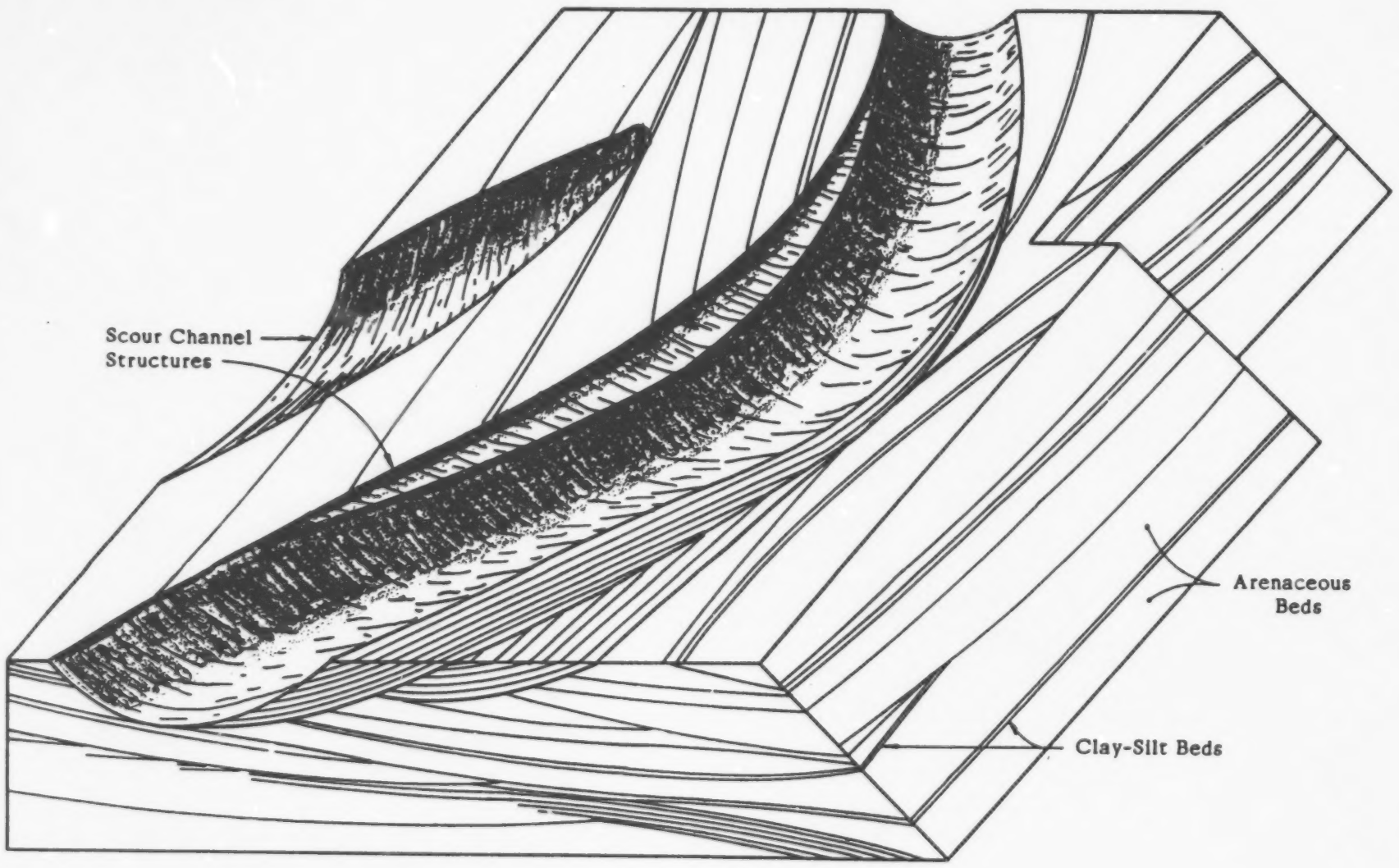
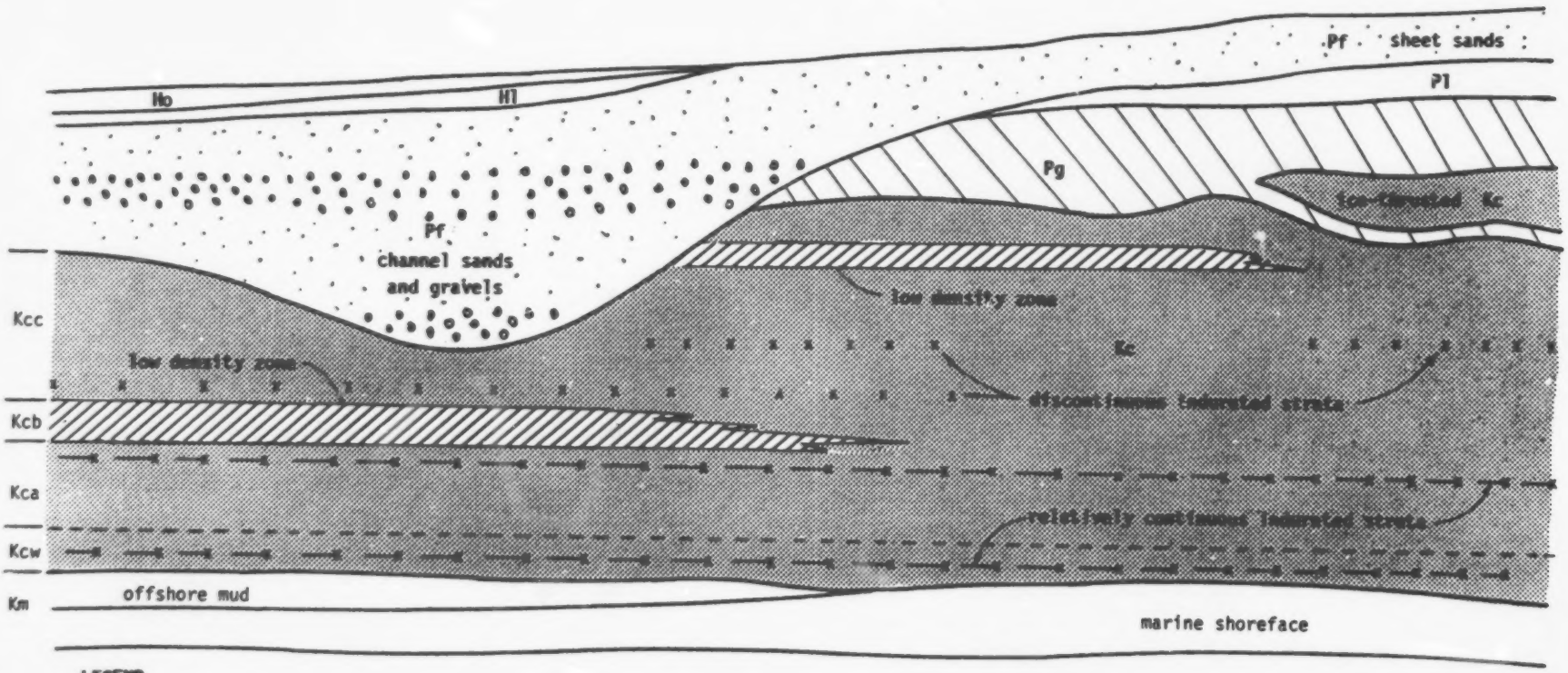


FIGURE 7 : ISOMETRIC VIEW OF TYPICAL STRUCTURES WITHIN THE ESTUARINE FACIES OF THE MCMURRAY FORMATION

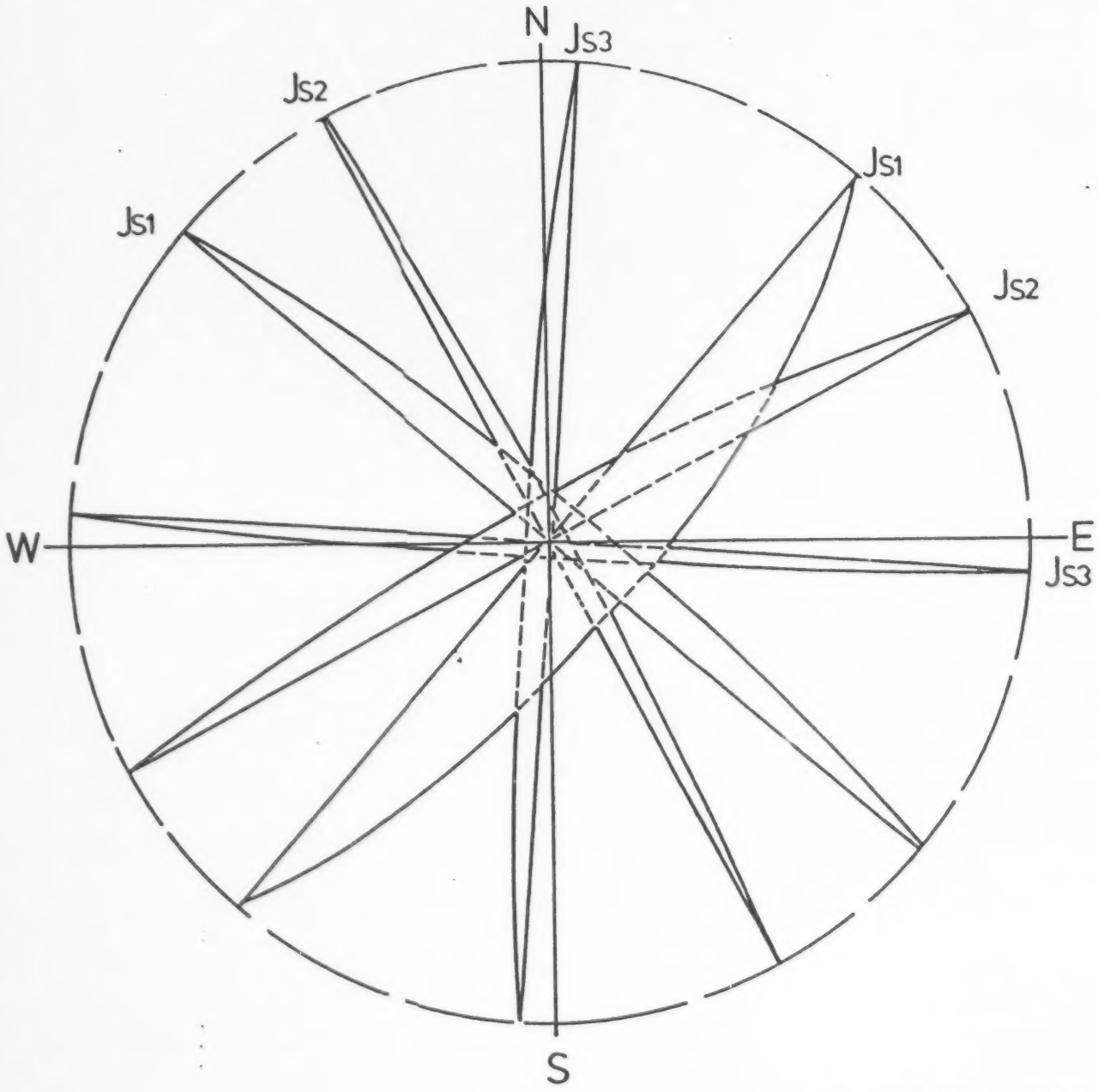
(Schematic - Not to Scale)



LEGEND

Ho - Holocene organic (muskeg)
Hl - Holocene lacustrine (clay)
Pf - Pleistocene fluvial (sand and gravel)
Pl - Pleistocene lacustrine (clay)
Pg - Pleistocene glacial (till)
Kc - Clearwater Formation (clayshale)
Kcw - Wabiskaw Member (interbedded clayshale and fine grained sand)
Kca, Kcb, etc. - informal clayshale units (correlation generally possible)
Km - McMurray Formation (oil sands)

FIGURE 8 : CROSS-SECTION ILLUSTRATING TYPICAL OVERBURDEN UNITS ENCOUNTERED IN THE ATHABASCA OIL SANDS



JOINT SETS

Js1 = 42°-132°Az-74°SE
Js2 = 63°-153°Az-84°NW
Js3 = 5°-95°Az-86°W

FIGURE 9 : STEREOGRAPHIC PROJECTION OF PREFERRED ORIENTATION OF JOINTS IN THE McMURRAY FORMATION

(after Khan, Nichols & Handford, 1980)

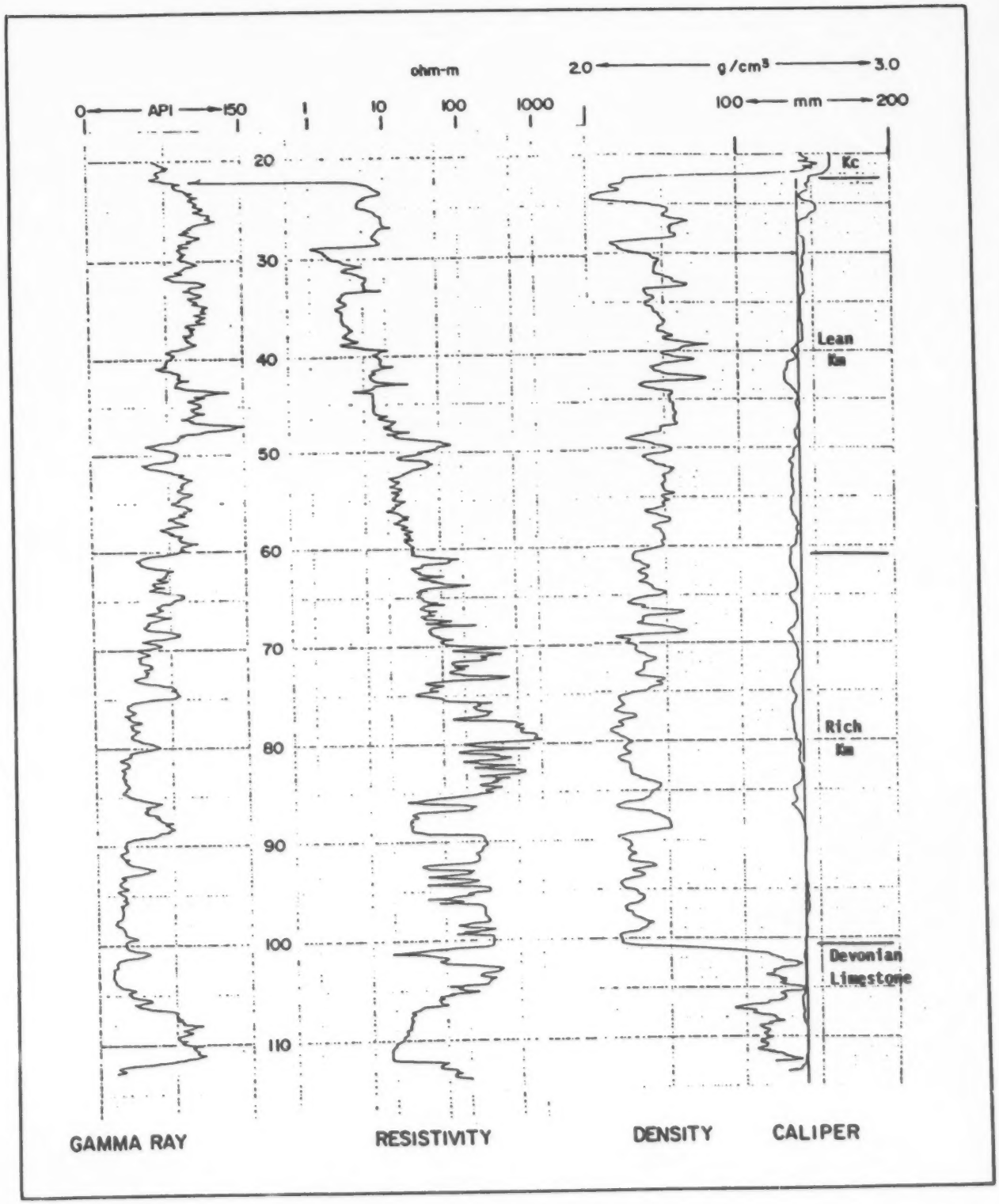


FIGURE 10: PHYSICAL PROPERTIES OF OIL SANDS SECTION

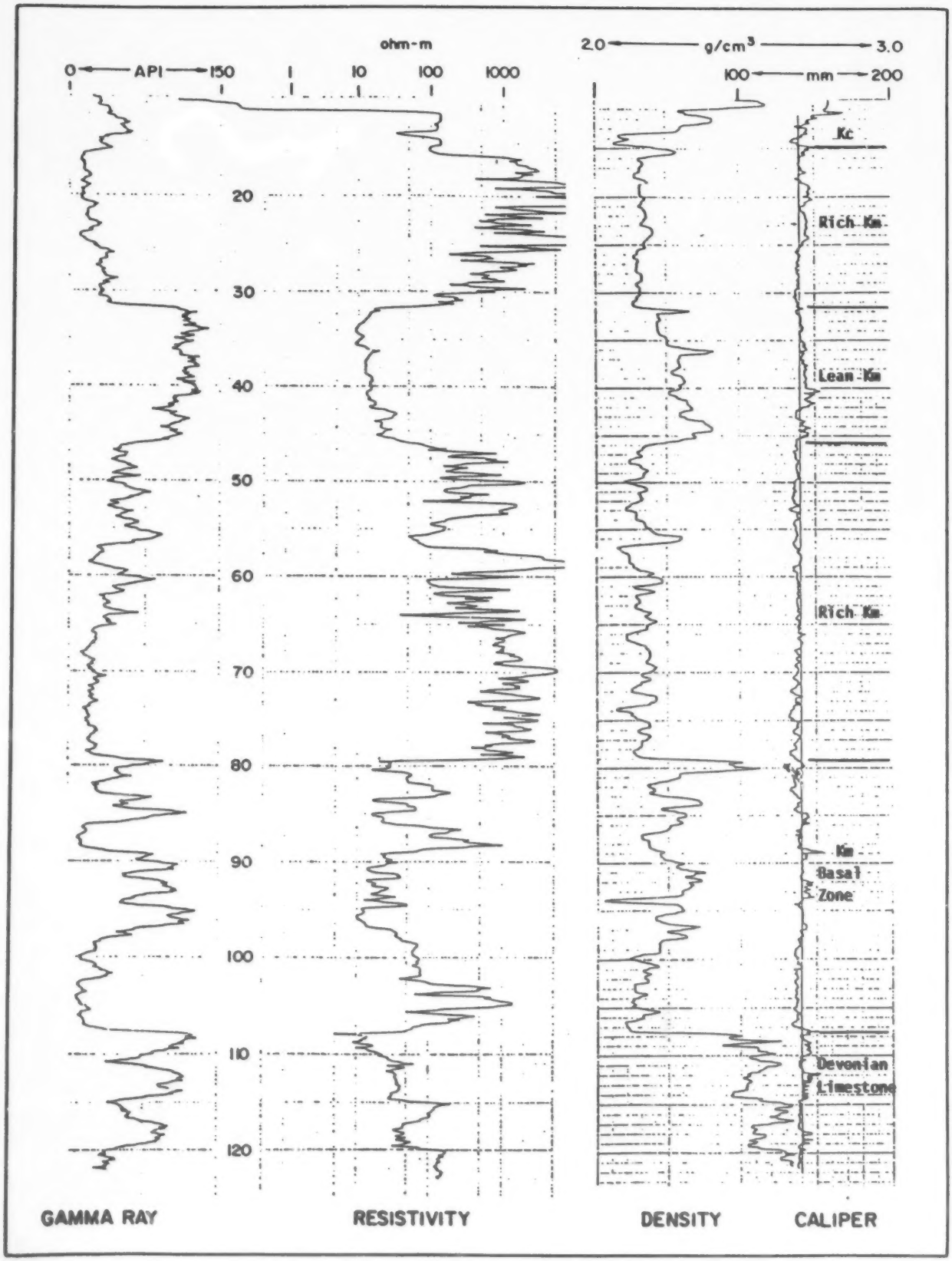


FIGURE 11: PHYSICAL PROPERTIES OF OIL SANDS SECTION

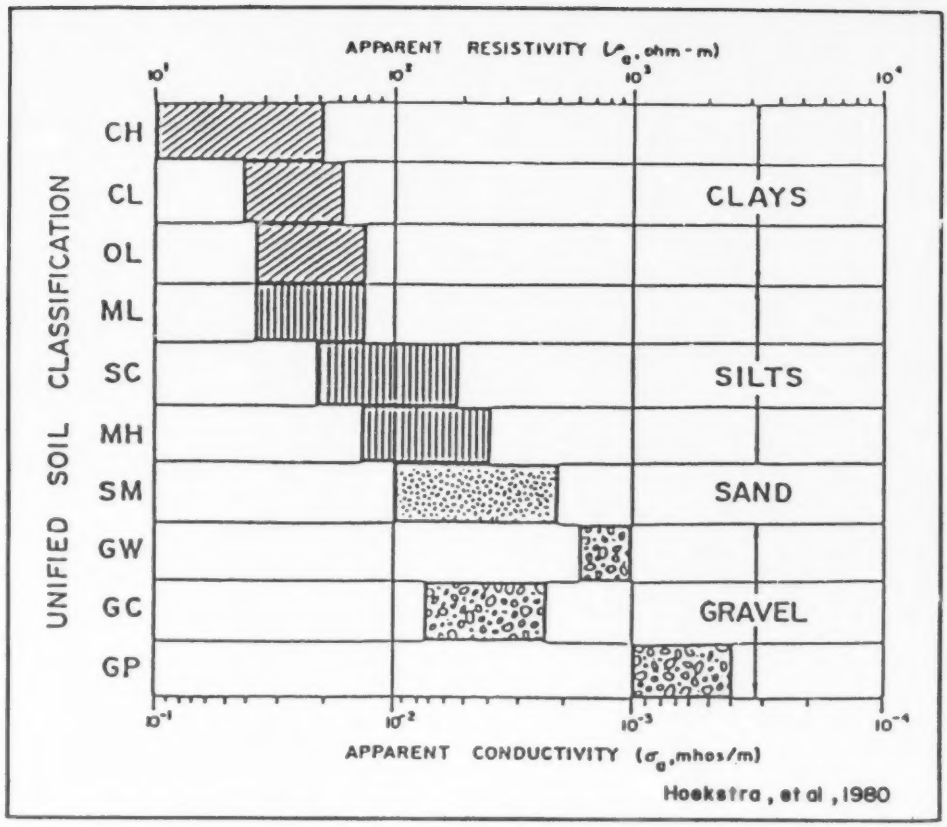


FIGURE 12: RESISTIVITY RANGES FOR SEVERAL SOIL TYPES

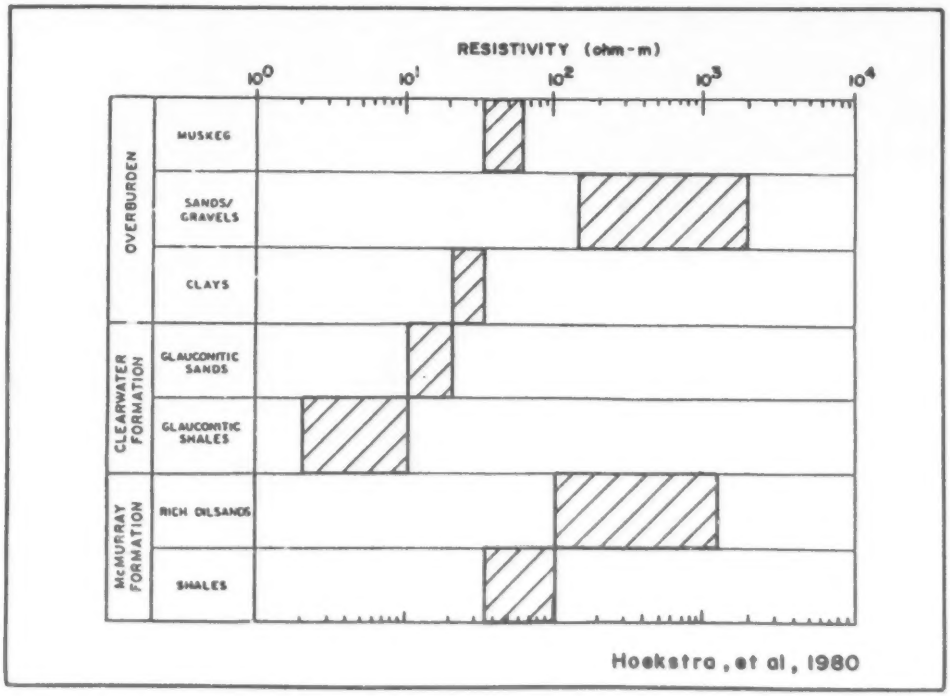


FIGURE 13: RESISTIVITY RANGES FOR DIFFERENT FORMATIONS ENCOUNTERED IN McMURRAY AREA

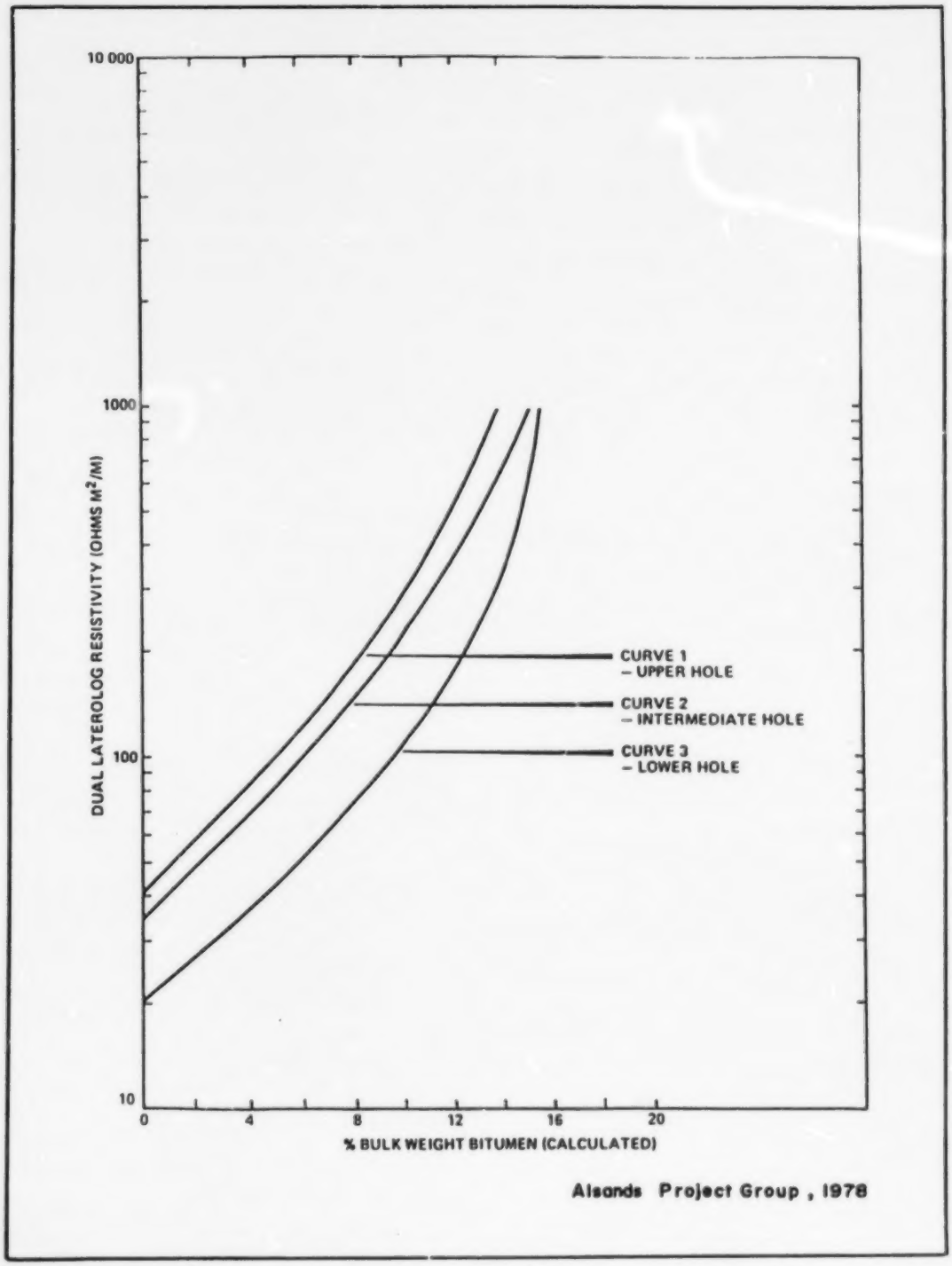


FIGURE 14: DUAL LATEROLOG RESISTIVITY VS. PERCENT BULK WEIGHT BITUMEN (CALCULATED)

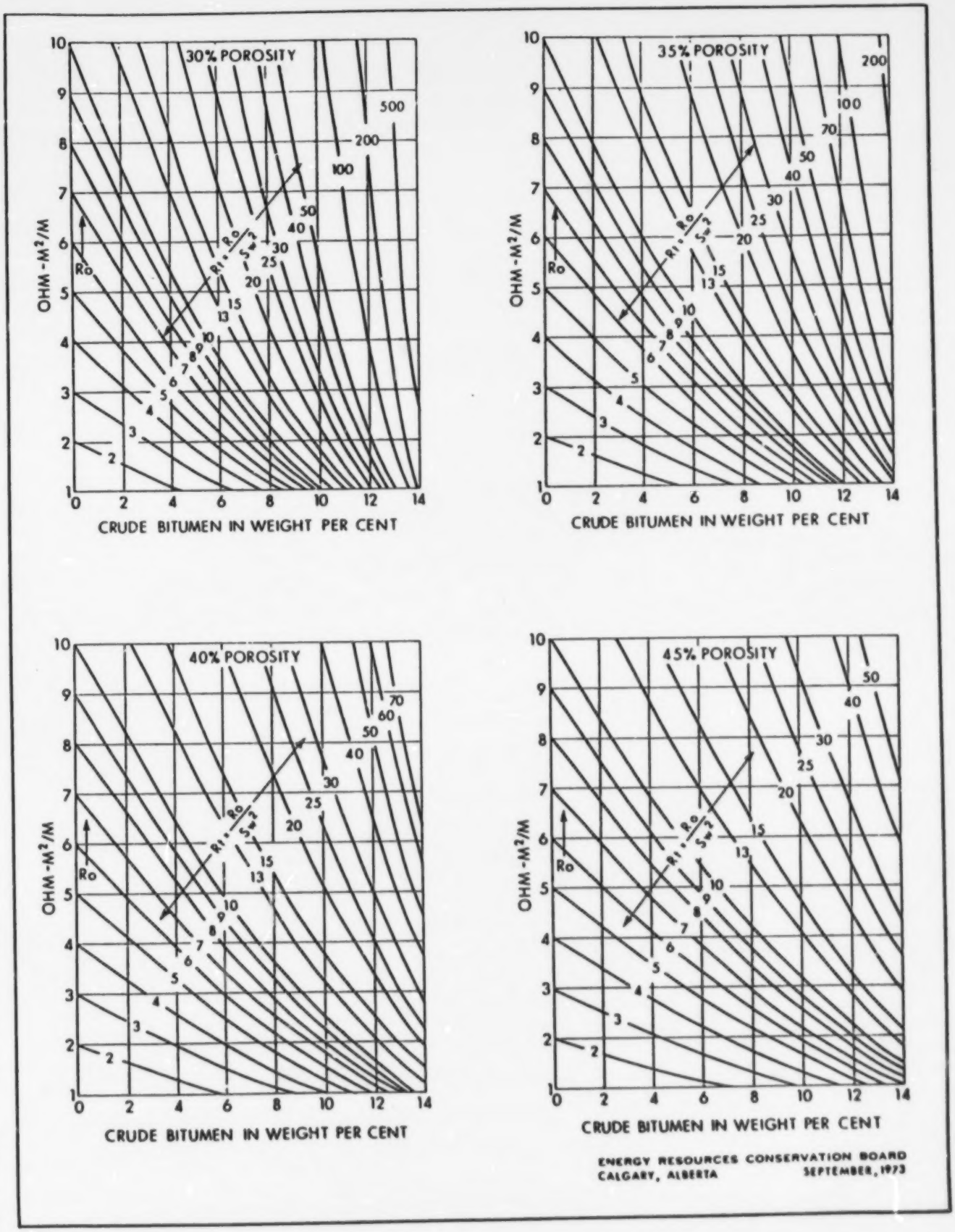


FIGURE 15: CRUDE BITUMEN SATURATION-RESISTIVITY-POROSITY RELATIONSHIP

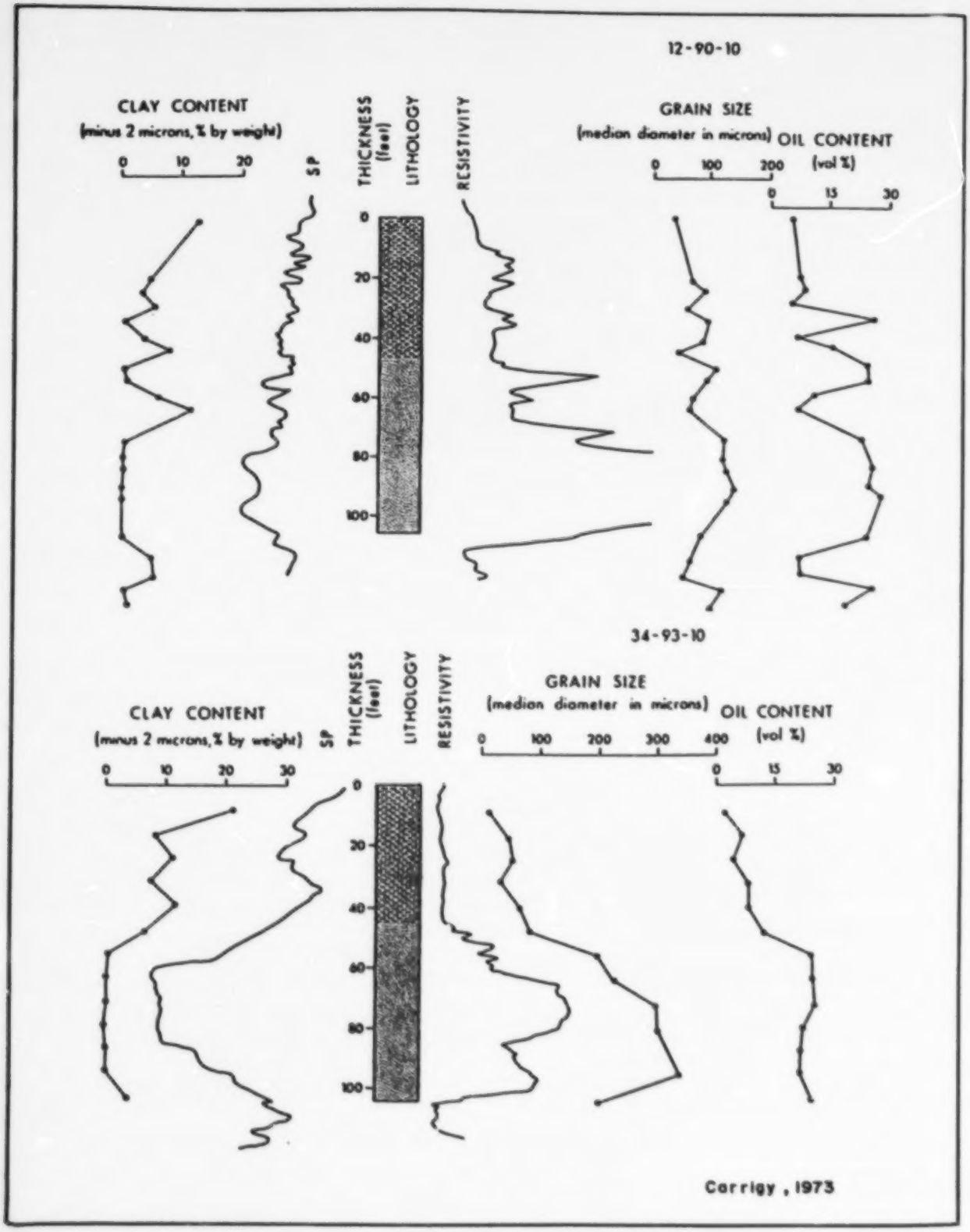


FIGURE 16: TYPICAL LITHOLOGICAL PROPERTIES AND GEOPHYSICAL RESPONSES OF TWO OIL SANDS CORES

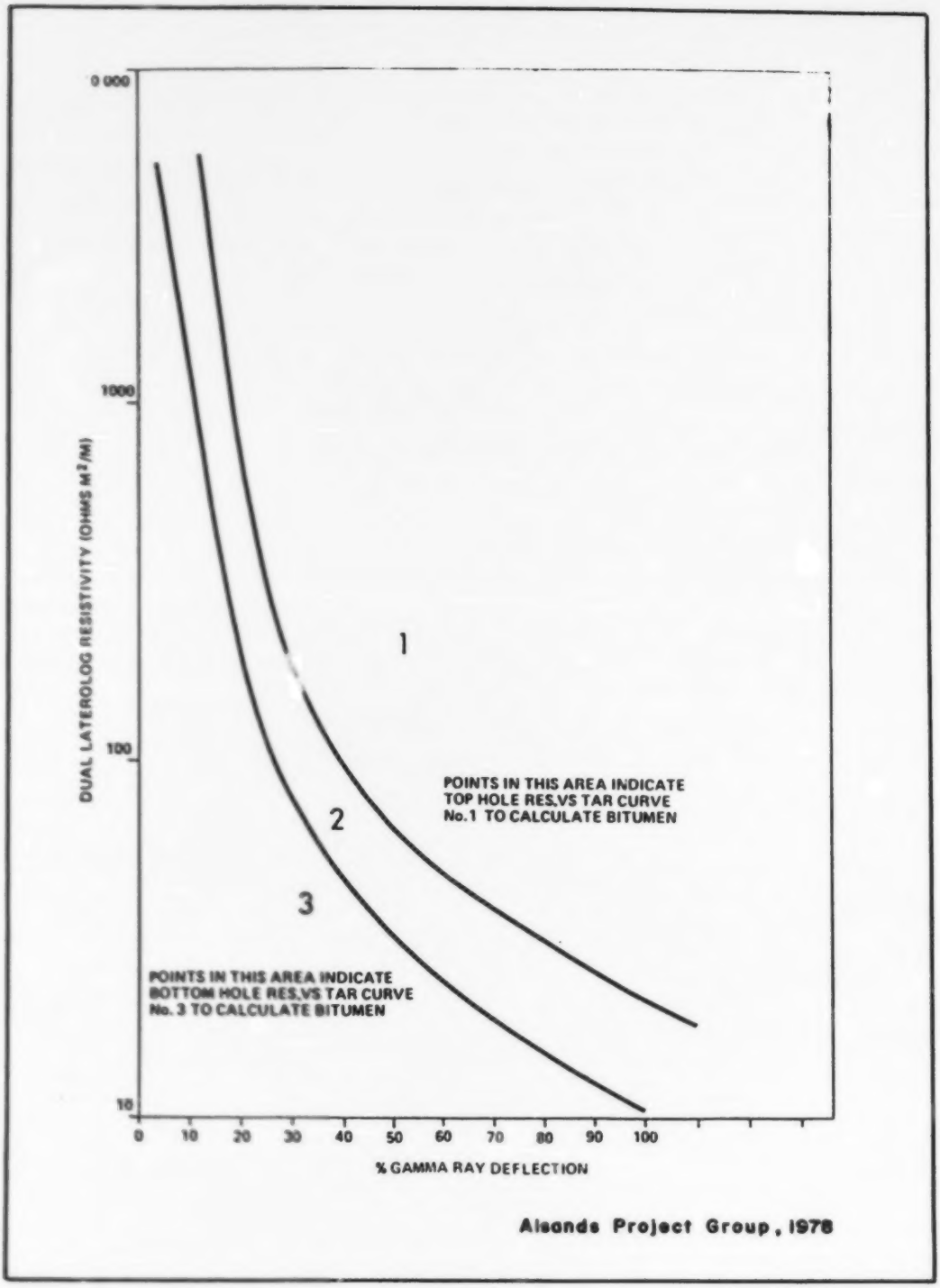


FIGURE 17: RESISTIVITY VS. GAMMA RAY DETERMINATION OF CURVE USED TO CALCULATE BITUMEN CONTENT

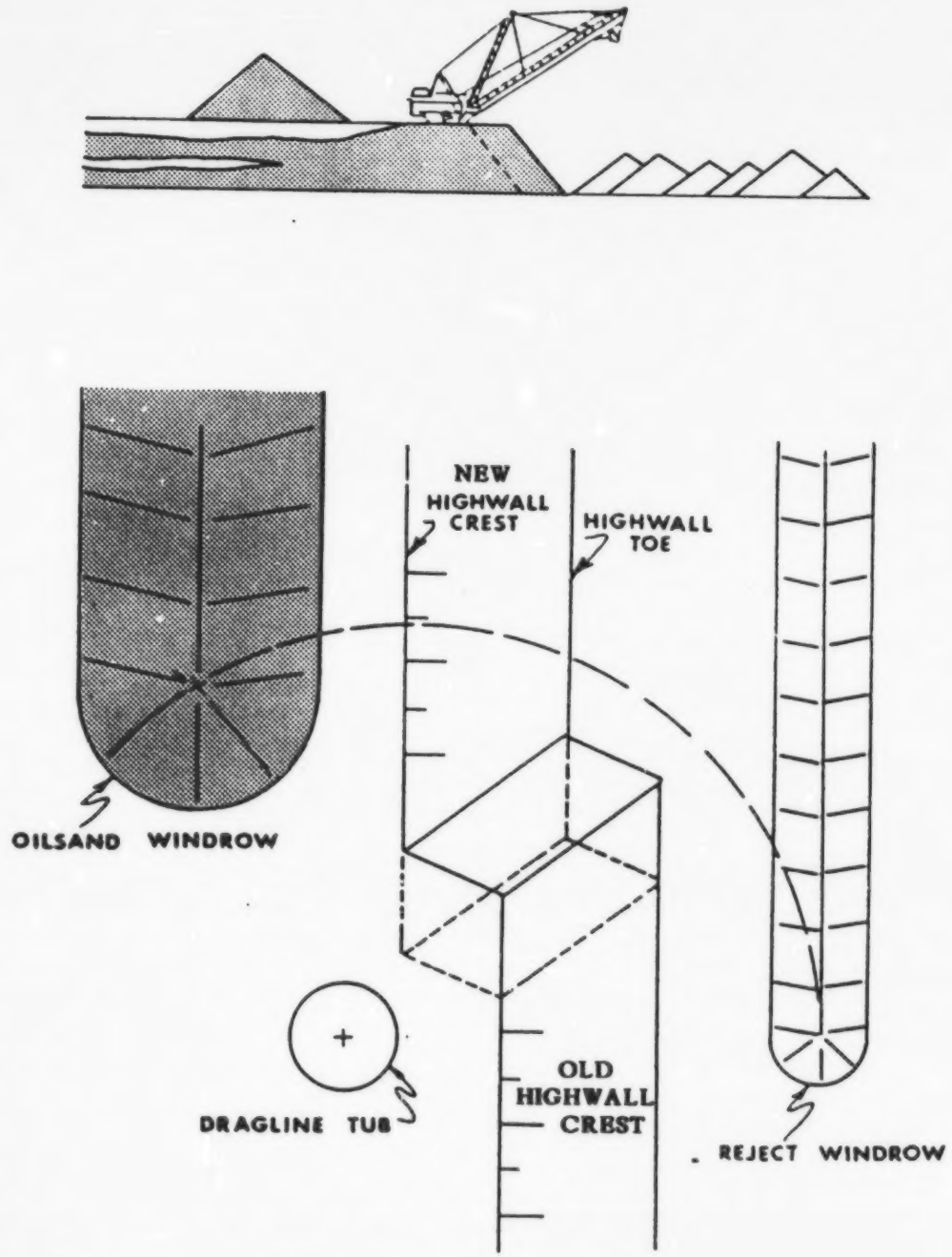
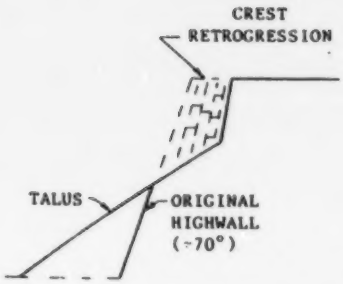
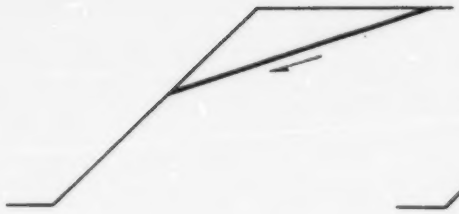


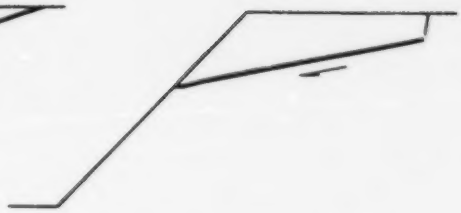
FIGURE 18 : SCHEMATIC OF SYNCRUDE DRAGLINE MINING METHOD



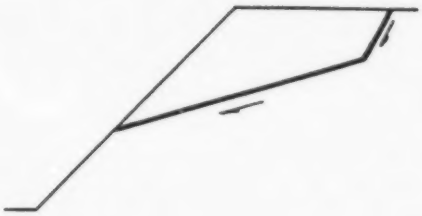
(A) SLABBING/TOPPLING FAILURE



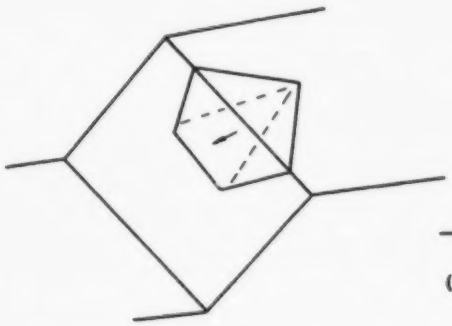
(B) BLOCK FAILURE - SINGLE SHEAR PLANE



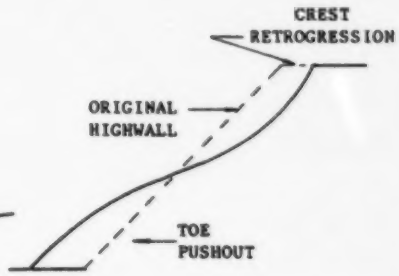
(C) BLOCK FAILURE - SINGLE SHEAR PLANE WITH TENSION CRACK



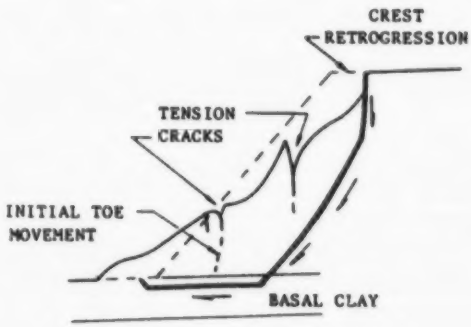
(D) BLOCK FAILURE - MULTIPLE SHEAR PLANE



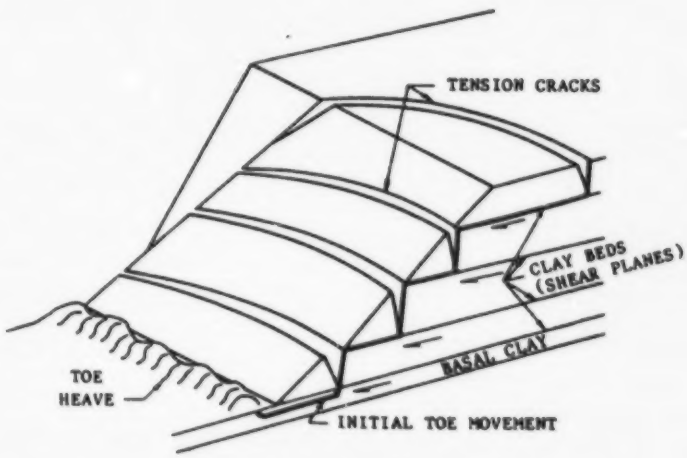
(E) BLOCK FAILURE - WITH CONJUGATE JOINT PLANES



(F) HIGHWALL TOE BULGING



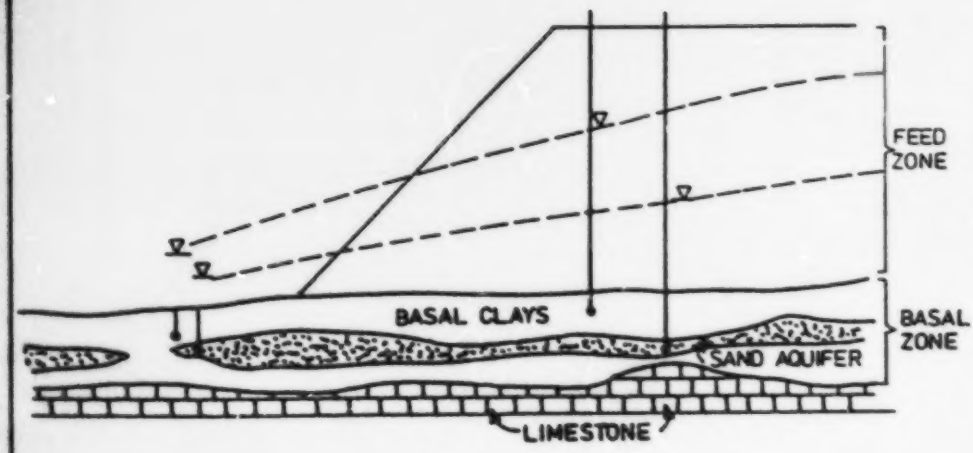
(G) PROGRESSIVE BASAL FAILURE



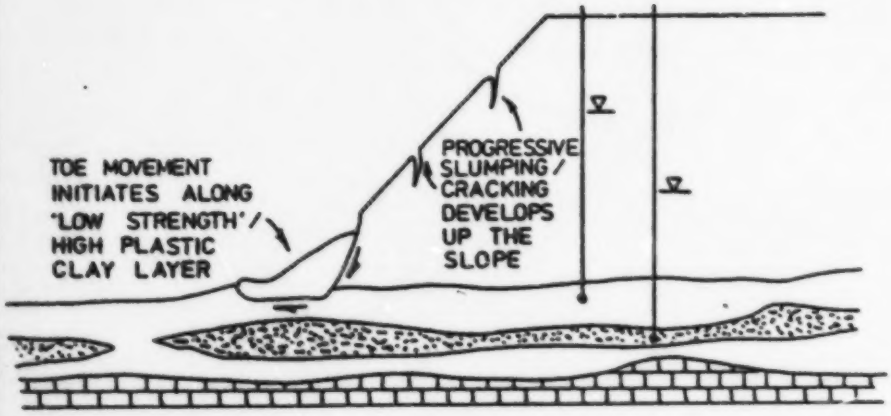
(H) PROGRESSIVE BASAL FAILURE - MULTIPLE BLOCK

FIGURE 19: MECHANISMS OF HIGHWALL INSTABILITY IN OIL SAND MINING

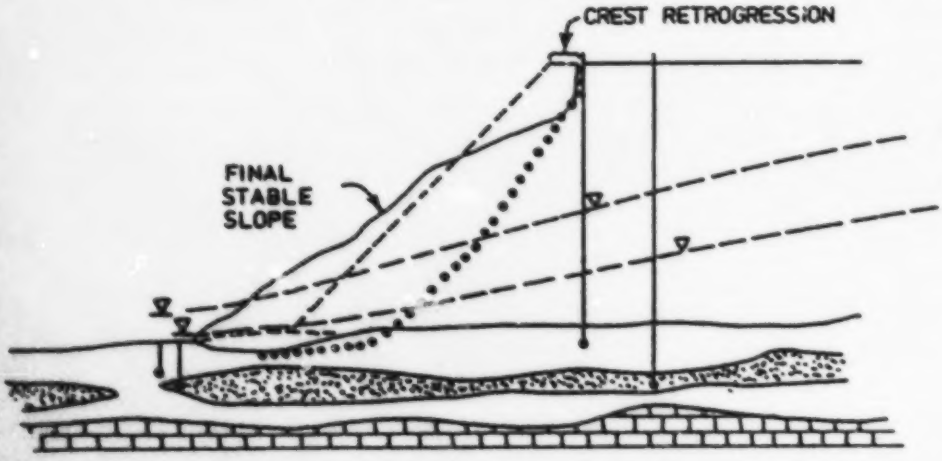
(Modified after Khan, Nichols and Handford, 1980)



INITIAL SLOPE – ALTHOUGH SAND AQUIFER DEPRESSURIZED, PORE PRESSURES WITHIN BASAL CLAYS REMAIN HIGH DUE TO LOW PERMEABILITIES.


TOE MOVEMENT INITIATES ALONG 'LOW STRENGTH' / HIGH PLASTIC CLAY LAYER
PROGRESSIVE SLUMPING / CRACKING DEVELOPS UP THE SLOPE

TOE MOVEMENT INITIATES ALONG 'LOW STRENGTH' / HIGH PLASTIC CLAY LAYERS WITH HIGH PORE PRESSURES. TOE MOVEMENT CAUSES PROGRESSIVE CRACKING AND SLUMPING IN UPPER PART OF SLOPE.



SLOPE CONTINUES TO RETROGRESS BACK UNTIL STABLE SLOPE IS REACHED WITH RESULTANT LOWER PORE PRESSURES.

FIGURE 20 : OBSERVED MODE OF PROGRESSIVE BASAL FAILURE AT THE SYNCRUDE MINE

(Modified after Khan, Pair and Cuddy, 1982)

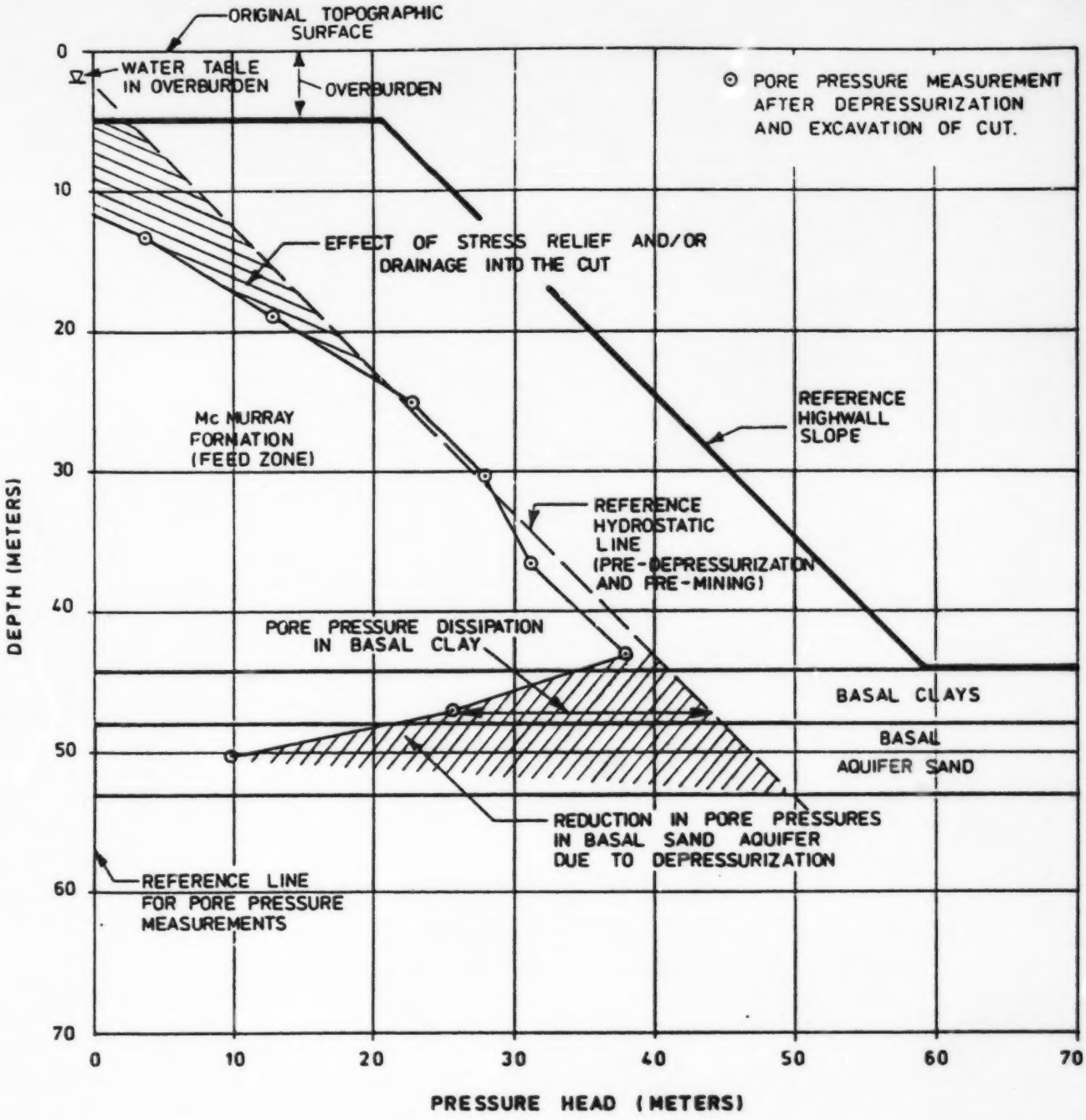


FIGURE 21 : TYPICAL PORE PRESSURE DISTRIBUTION THROUGH McMURRAY FORMATION SHOWING EFFECT OF MINING AND DEPRESSURIZATION (after Khan, Fair & Cuddy, 1982)

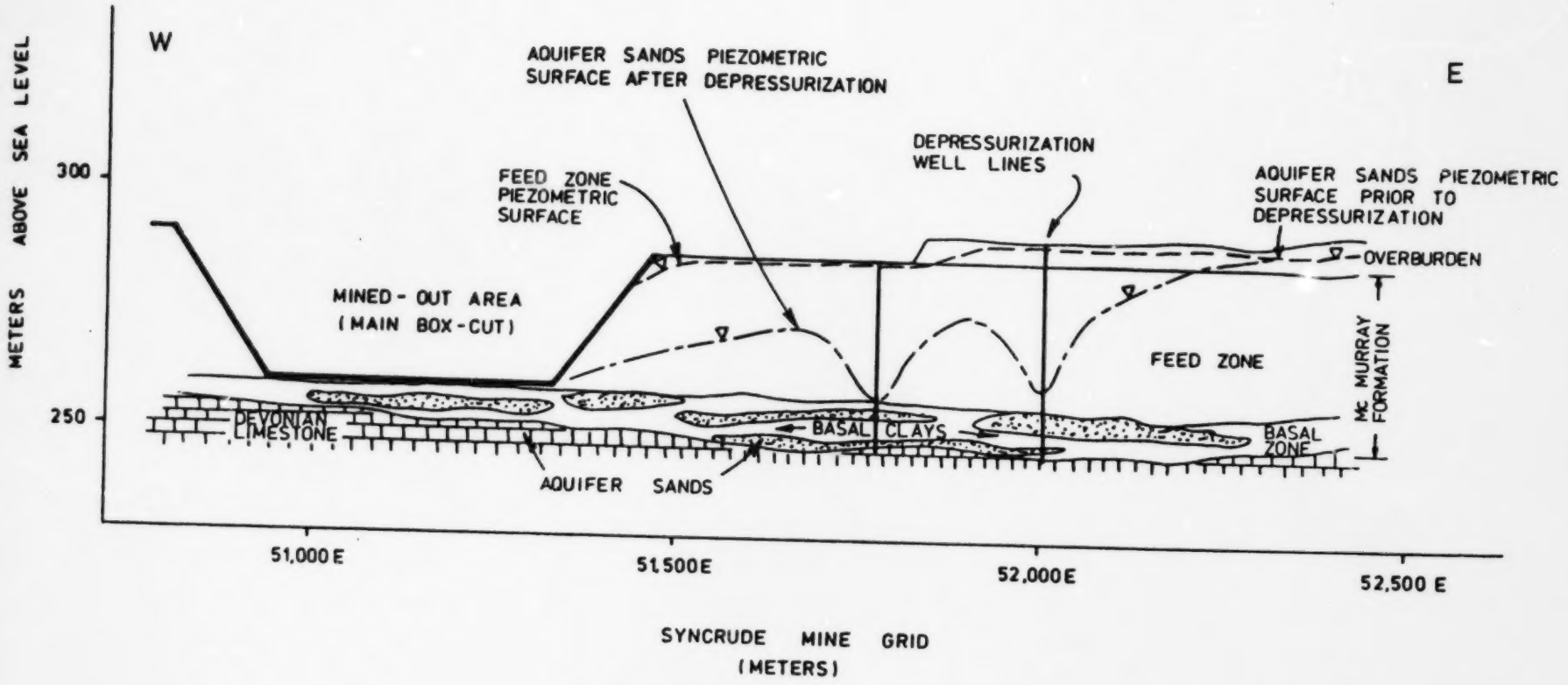


FIGURE 22 : DIAGRAMMATIC CROSS-SECTION OF SYNCRUDE MINE DEPRESSURIZATION
(after Khan, Fair & Cuddy, 1982)

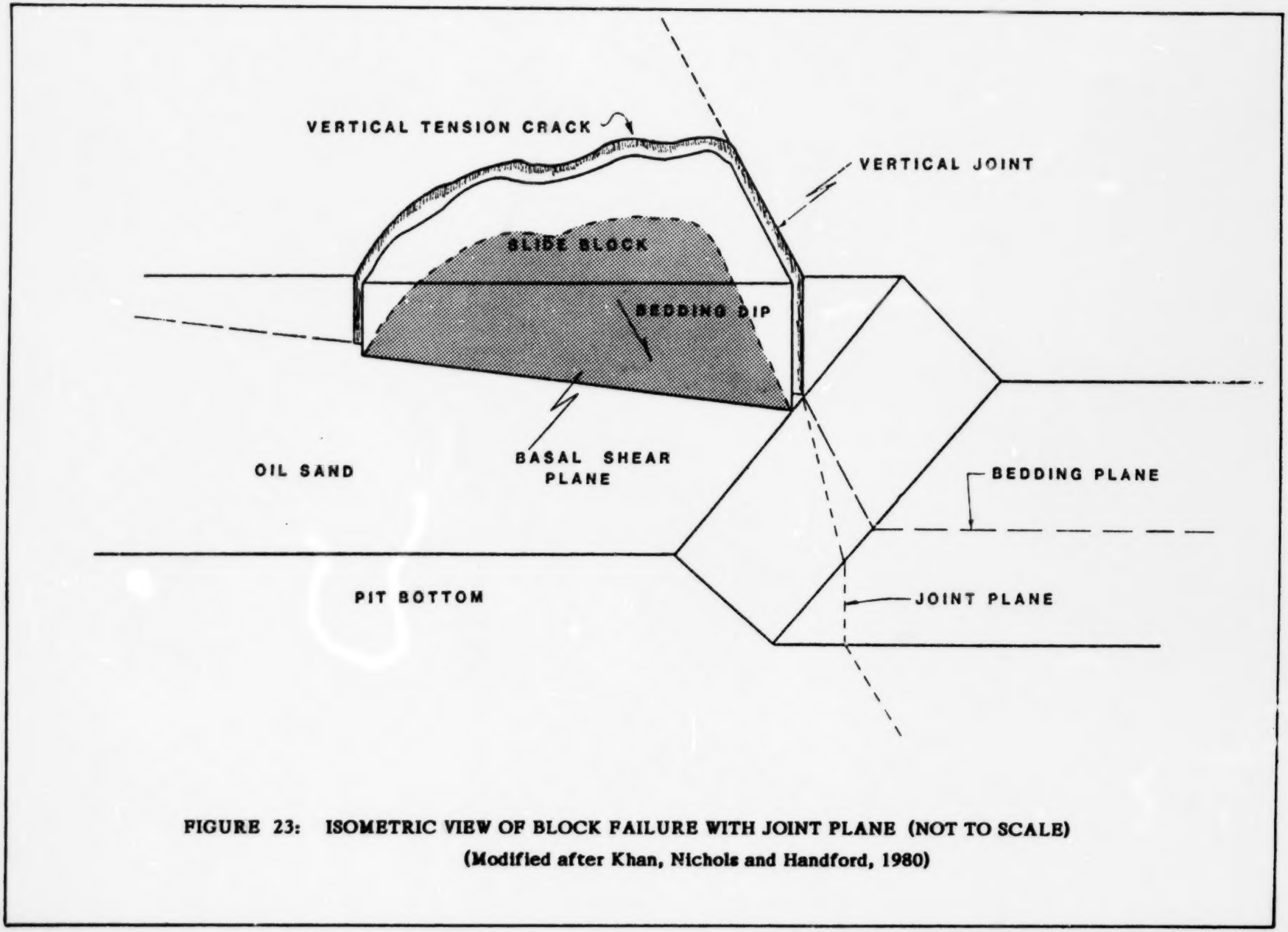


FIGURE 23: ISOMETRIC VIEW OF BLOCK FAILURE WITH JOINT PLANE (NOT TO SCALE)
(Modified after Khan, Nichols and Handford, 1980)

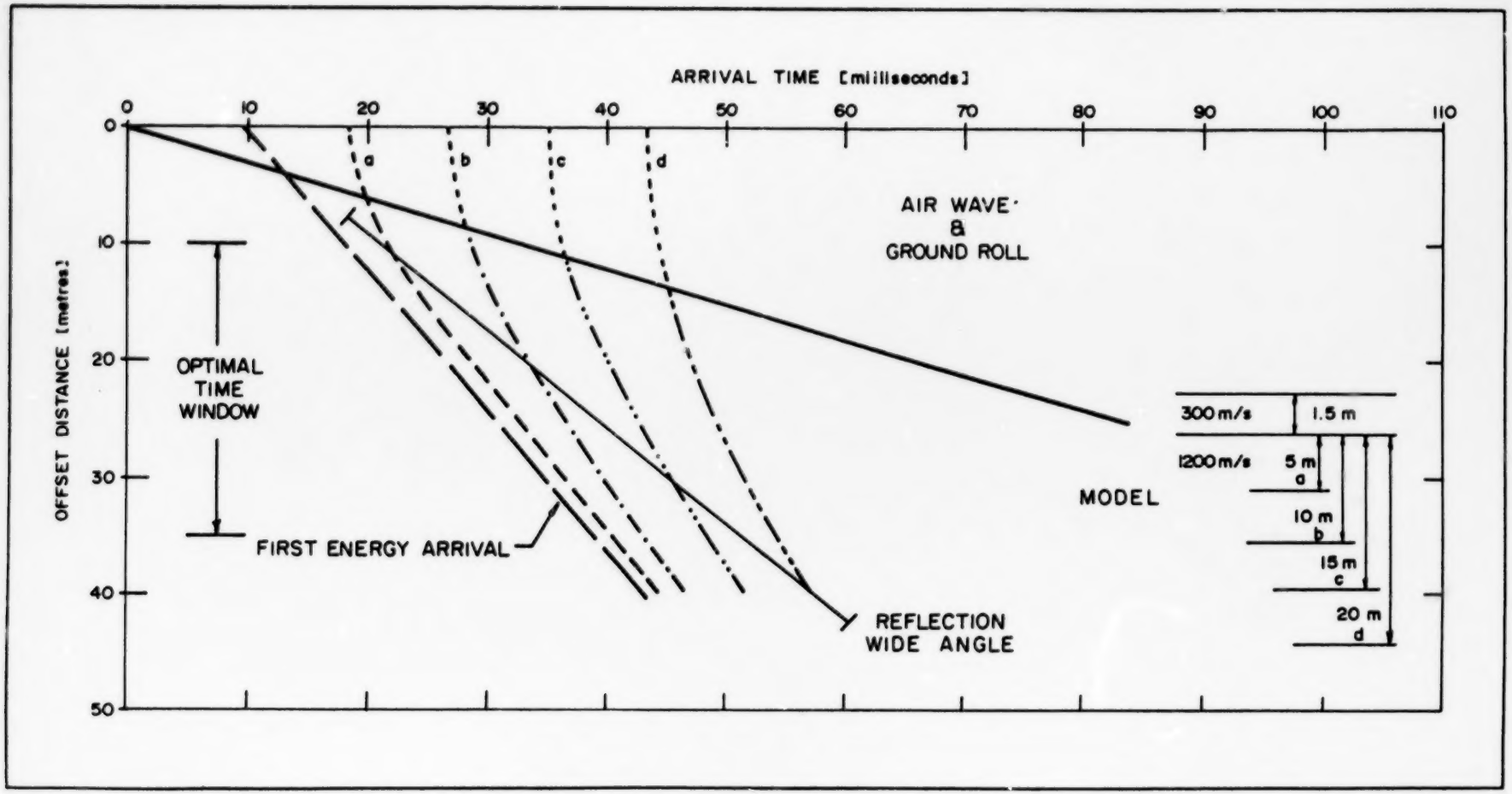


FIGURE 24: TIME DISTANCE GRAPH FOR SEISMIC RESPONSE MODELLING

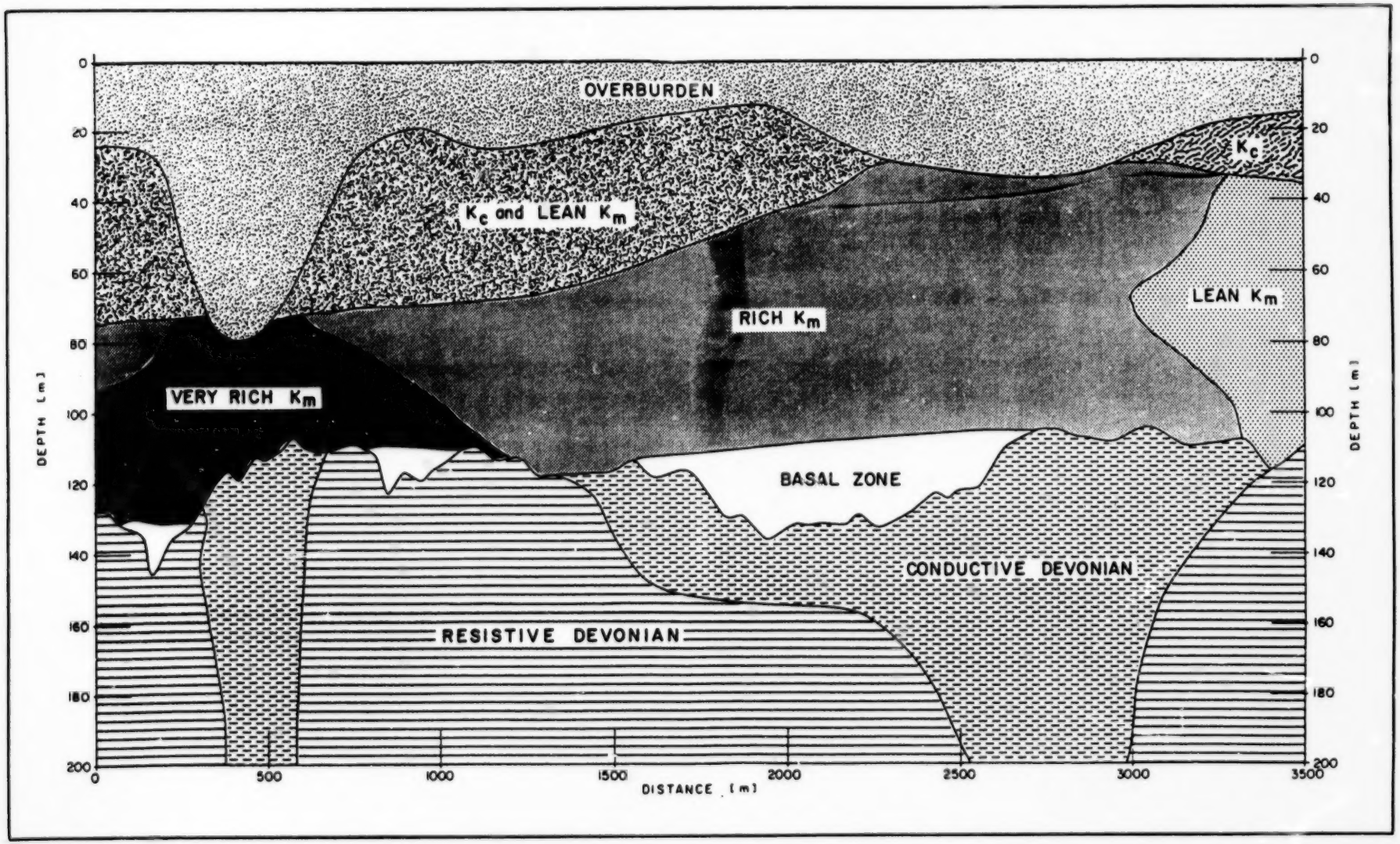


FIGURE 25: GEOPHYSICAL SECTION

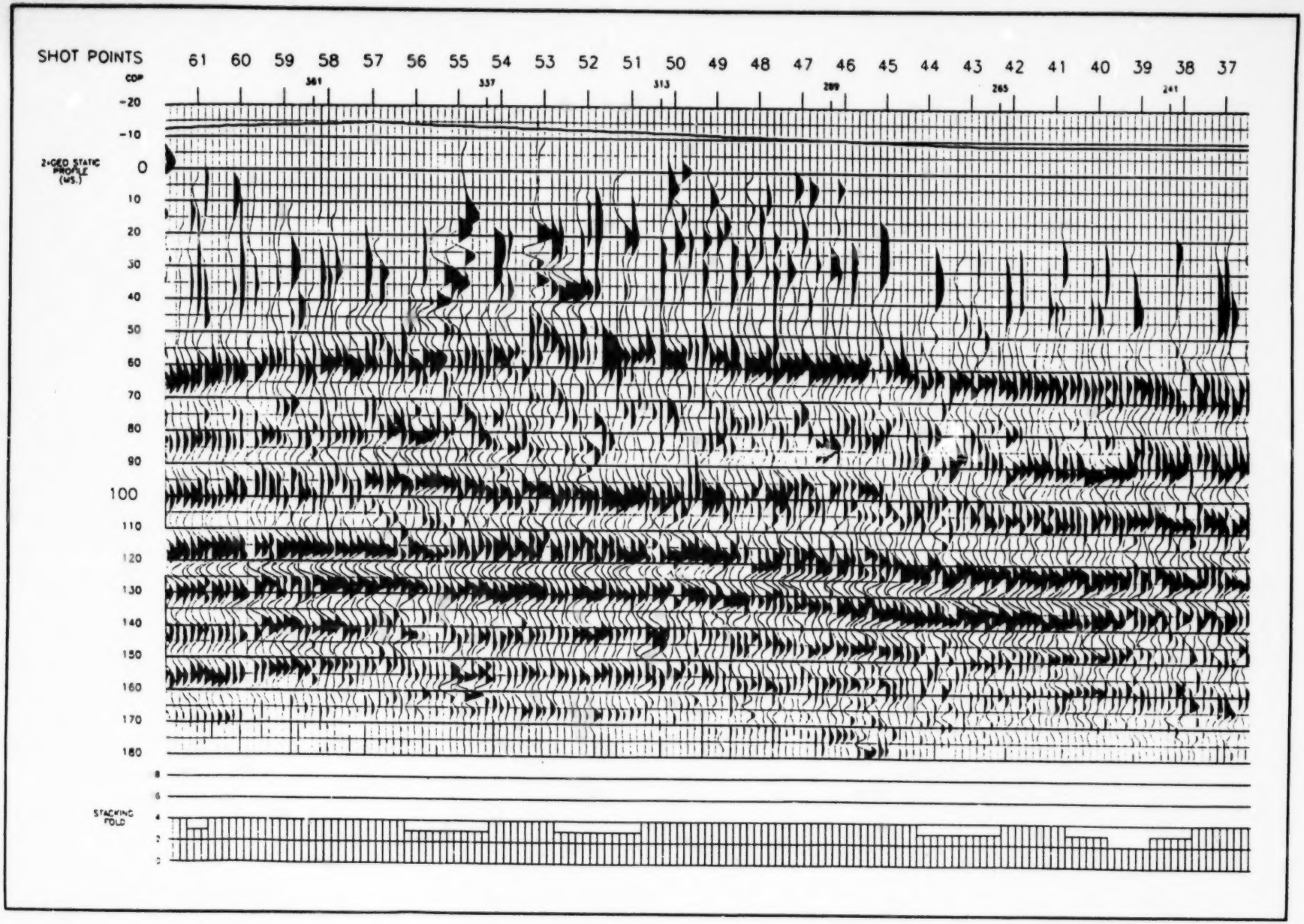


FIGURE 26: REFLECTION SEISMIC PROFILE

APPENDIX B

BASIC PRINCIPLES OF GEOPHYSICAL METHODS

APPENDIX B

1.0 BASIC PRINCIPLES OF GEOPHYSICAL METHODS

In surface geophysical methods, the measurement at the surface is a function of the cumulative response of all of the strata within the effective depth of exploration of the instrumentation employed. This differs drastically from borehole geophysical methods in which the measurements are performed in a close proximity to the individual strata under investigation. As a result, surface geophysical measurements must always be correlated to the existing subsurface information. This section briefly discusses the commonly used geophysical methods and their general applicability in the surface mineable oil sands environments.

1.1 Seismic Methods

There are three types of seismic surveys that have been applied in the Alberta surface mineable oil sands areas. These include:

1) refraction seismic
2) reflection seismic
3) crosshole seismic

Both the refraction and reflection seismic techniques are carried out from the ground surface. Cross hole seismic surveys require that sources and sensors are placed in relatively closely spaced drill holes. In this section, only surface geophysical methods are discussed.

Seismic methods exploit the laws of elastic energy propagation through subsurface materials. All energy propagation is in the form of body waves or surface waves. Body waves are of two types, compression waves and shear waves. Compression waves cause particle displacements parallel to the direction of propagation. Shear waves cause particle displacement perpendicular to the direction of propagation. Shear waves necessarily propagate at a lower velocity than compression waves. Surface waves, on the other hand, generally exhibit particle

motions that are elliptical, being both parallel and perpendicular to the horizontal direction of energy flow. Surface waves are restricted to relatively thin zones beneath the ground surface.

The paths of propagation from source to geophones are shown in Figure B-1 for a simple two-layer case for direct, reflected, and critically refracted waves. It is evident that only the refracted ray carries information about the refracting surface.

The direct and reflected rays carry information concerning the overburden.

1.1.1 Refraction Seismic

The field procedures of refraction seismic prospecting, the data processing required, and the accuracy that can be obtained can best be illustrated by a simple two-layer situation of overburden overlying bedrock.

The acquisition proceeds in the manner indicated in Figure B-2. Generally, a spread of 12 to 24 geophones are laid out in a line. The spacing between geophones depends mainly on the required exploration depth. For each spread of geophones several shot points are recorded.

The accuracy of determining depth to bedrock from refraction seismic prospecting depends on the manner of data acquisition. This can be illustrated from Figure B-3 which shows the arrival times from two shot points, A and B, from opposite ends of a spread of 12 geophones. These records are typical of those obtained in overburden exploration. It is clearly difficult to determine velocities of bedrock and overburden from either the record from shot A or B. The main reason for this is the irregular nature of the bedrock surface. In Figure B-3 the difference in arrival times at each geophone from shot A and B is plotted. This plot shows that the value of T_B-T_A for 5 geophones falls on a straight line with little scatter. It can be shown that the slope of this line is related to the bedrock velocity by the relationship $2/V_2$.

Figure B-3 can also be used to determine which geophones record first arrivals refracted from the bedrock surface. Points that fall on the line with a slope of $2/V_2$ record a first arrival refracted from the bedrock, points off the line do not.

Next, the delay time defined in Figure B-3 is calculated for each geophone showing a first arrival refracted from the bedrock. Subsequently, depth to bedrock is computed in the manner shown in the figure.

The illustration of Figure B-3 can also be used to discuss parameters that determine accuracy of refraction seismic prospecting. The figure illustrates that reverse shooting is an absolute requirement for obtaining good data in refraction seismic prospecting. Often the reason for using seismics is because irregular or dipping surfaces are expected, and in such situations only apparent, not true, velocities can be obtained from single ended time-distance plots.

Depth to bedrock can be computed only under the geophones recording a first arrival refracted from the bedrock (5 geophones in Figure B-3). This number can be increased by recording shots which are offset a greater distance from the end of the spread. As a general rule, a first arrival refracted from the bedrock, may be recorded if the shot to geophone distance exceeds about 4 times the depth to bedrock.

Figure B-3 shows that three parameters determine the depth to bedrock for a simple two-layer case, namely, V_1, V_2 and the delay time ΔT. V_2 and ΔT can generally be determined to an accuracy of 10 percent. The largest source of error in determining the depth to the refractor is the overburden velocity, V_1, since overburden velocity will vary along a profile. To obtain a better determination of V_1 and its variation, intermediate shots should be recorded.

1.1.2 Reflection Seismic

The reflection seismic method is highly developed for application to deep exploration targets. There are a number of complicating factors which hamper the application to exploration in the shallow subsurface.

The greatest complication arises in trying to identify reflected events amidst energy arriving via a variety of other transmission modes. The wave types briefly responsible for interference include a direct wave through air, refracted waves, and ground roll (Rayleigh surface waves). Generally, these interfering wave modes propagate at different velocities. A time window in which reflections can be identified is generally present between the onset of refracted waves and the arrival of surface (or air) waves. The width of this window (the depth of exploration) is a function of the source to sensor separation. Practical limits on the size of the time window are imposed by the attenuation of signal strength, which increases with travel path length, and the asymptotic merging of reflected and refracted arrivals at large source separation (wide angle reflections). Figure B-4 illustrates the separation of the transmitted wave forms (time window).

For shallow reflections, a relatively large proportion of the total reflected travel time occurs in the low velocity near surface layers representing unconsolidated materials. Accurate determinations of the depth to reflecting boundaries require that the thickness and velocity of near surface layers be known.

The reflection seismic method has the advantage of being able to probe to depths much larger than the source to sensor separation (good lateral resolution) and the ability to sense the presence of a subsurface boundary characterized by a velocity inversion, i.e. a decrease in material velocity on the down side of a subsurface boundary.

1.2 Electrical and Electromagnetic Methods

Electrical and electromagnetic methods make use of the differences in electrical resistivities of different formations. However, the suitable application of electrical methods depends not only on resistivity contrasts, but also on the depth of occurrence of the strata to be mapped and the resistivities and thicknesses of all layers above that strata.

1.2.1 Galvanic Methods

Direct current soundings are one of the oldest and most commonly used methods for determining earth resistivity. A description of the various electrode configurations can be found in Keller, et.al., 1966.

One of the most commonly used electrode arrays is the Schlumberger configuration. For the Schlumberger configuration, current is driven into the ground through one pair of electrodes (I_1 and I_2). The potential established in the earth by this current is measured with a second pair of electrodes (P_1 and P_2). To study the variation in resistivity with depth, the spacing between the current electrodes is altered. Figures B-5a and B-5b show the distribution of current flow at two electrode spacings. At close electrode spacing (Figure B-5a), the currents dominantly flow near the surface and the potential field is virtually not influenced by the second layer. The apparent resistivity measured approximates the resistivity of the first layer. With increased spacing, part of the current flow is located in deeper layers. The potential field then shows the influence of the deeper layers.

The DSC method is effective for determining the presence of electrically resistive strata at depth in a section, since resistive strata present a barrier to current penetration.

Since current electrode separations of 4 to 5 times the depth of exploration are normally utilized, the method is dependent on the lateral homogeneity in earth resistivity.

1.2.2 Fixed Frequency Electromagnetic Induction (EM)

In the EM method, eddy current flow is induced in the ground by the time varying magnetic field of a vertical or horizontal magnetic dipole transmitter operating at a fixed frequency. This eddy current flow induces a secondary magnetic field which, together with the primary field, is sensed by a similar receiver dipole. The ratio of the primary and secondary fields is related to the resistivity of the subsurface.

The instrument parameters, frequency and coil separation, are selected in a manner so that the operation can be described by the low induction number approximation over a relatively large range of terrain resistivity. In this sense, each induced eddy current loop is independent of the others and the measured signal can be thought of as a linear superposition of the responses of strata within the exploration range of the array used.

The effective exploration depth of the EM equipment can be varied by changing loop spacing, loop orientation (vertical or horizontal), and/or the height above the ground. The effective depth of exploration is a relative value only. It is usually taken to be the depth at which the primary field would fall to 1/e (≈37%) of its value at the ground surface, over terrain homogeneous in resistivity stratification of the ground where EM data to a number of exploration depths are available.

When terrain resistivity is less than 15 ohm-m, the low induction number approximation is no longer valid. In this instance EM measurements indicate terrain resistivities that are greater than true values. Horizontal loop configurations at large loop separations are most seriously affected by low terrain resistivity.

1.2.3. Transient Electromagnetic Sounding

A transient system consists of a transmitter (T) and receiver (R). Different arrays of T and R may be used as shown in Figure B-6. The physical basis of the method will be illustrated for the array using a non-grounded loop as a transmitter. The non-grounded loop is energized by current pulses (Figure B-7). During time-on, when the current is constant in the loop, the magnetic field is invariant with time. There are no induced currents in the surrounding medium at this time. When the transmitter current is switched off, induced currents arise in the ground due to rapid changes of the primary magnetic field in accordance with Faraday's Law. During the time-off interval, the induced currents in the ground are the only sources for the secondary magnetic field shown in Figure B-7.

The behavior of the ground currents as a function of time and depth are illustrated in Figure B-8. The first instant after the transmitter current is switched off, the eddy current intensity is highest near the ground surface under the transmitter loop. As a result, the electromotive force in the receiver coil depends mainly on the resistivity of the upper layer. Figure B-8 shows that with increasing time the current maxima occur at increasing depth. As a result, with increasing time the electromotive force measured in the receiver will be influenced more by the properties of deeper layers. The depth of investigation thus increases as a function of time.

1.2.4 Magnetotelluric Surveys

In the magnetotelluric method, naturally existing electromagnetic fields are used to determine the geoelectric section of the subsurface. These natural electromagnetic fields contain appreciable energy over a wide spectrum of frequencies.

At an observation point where subsurface information is sought, the horizontal components of both electric and magnetic fields, caused by either natural or manmade sources, are measured at a series of frequencies. From these measurements the surface impedance is computed, and the frequency spectrum of the surface impedance in turn provides information about the profile of electrical resistivity as a function of depth.

The depth of exploration is a function of frequency; the lower the frequency the deeper the exploration depth. The effective depth of exploration is related to the skin depth. The skin depth is defined by:

$$\delta = \sqrt{\frac{\rho}{\pi \mu_o f}}$$

where: δ is skin depth in metres
ρ is ground resistivity in ohm-metres
μ_o is magnetic susceptibility, 1.257×10^{-6} henry/m
f is frequency in hertz

In Figure B-9 skin depth is plotted as a function of frequency. With commercially available equipment, measurements can be made over a frequency band from 10^{-1} Hz to 10 khz, so that the exploration depth of magnetotelluric measurements can be several kilometres. Magnetotelluric methods have not been used to date in surface mineable oil sands. They do not appear to have application in the near future.

1.3 Other Methods

1.3.1 Gravity

In gravity prospecting, the anomalies in the earth's gravitational field caused by subsurface structures with different densities are measured. These differences are very small requiring careful data acquisition and processing.

The acceleration due to gravity is roughly 980 cm/sec^2 or 980,000 milligal. Gravity anomalies encountered in geophysical prospecting are often less than 10 milligal, and must generally be measured to an accuracy better than 0.1 milligal. To detect anomalies caused by the geologic feature to be mapped (e.g. scour channels), other factors effecting the earth's gravitational field locally must be taken into account.

These factors are:

1) elevation effect
2) intermediate layer effect (Bouguer anomaly)
3) terrain effect
4) latitude effect

Gravity surveys have not been routinely conducted in surface mineable areas. The potential applications of the gravity method have been achieved by other more cost effective methods which also rely on contrasts in density.

1.3.2 Magnetic

The earth's magnetic field resembles the field of a large bar magnet located in the centre of the earth. The magnetic lines of force are near horizontal at the equator and near vertical at the poles. The intensity of the field is approximately twice as large at the poles as at the equator.

Superimposed on the spatial variation of the earth's magnetic field are variations in time. Significant time variations with periods of seconds, minutes and hours, and are mainly due to the effects of solar winds.

The earth's magnetic field is locally influenced by the magnetic properties of rocks. Magnetic methods for geophysical exploration detect small anomalies in the total field caused by a variation in the subsurface. There are two sources for local variation in the magnetic fields due to rock properties. They are:

1) induced magnetization
2) remnant magnetization

During recent years, magnetic surveys have not been routinely used in surface mineable oil sands. For the Fort McMurray area they appear to have little application.

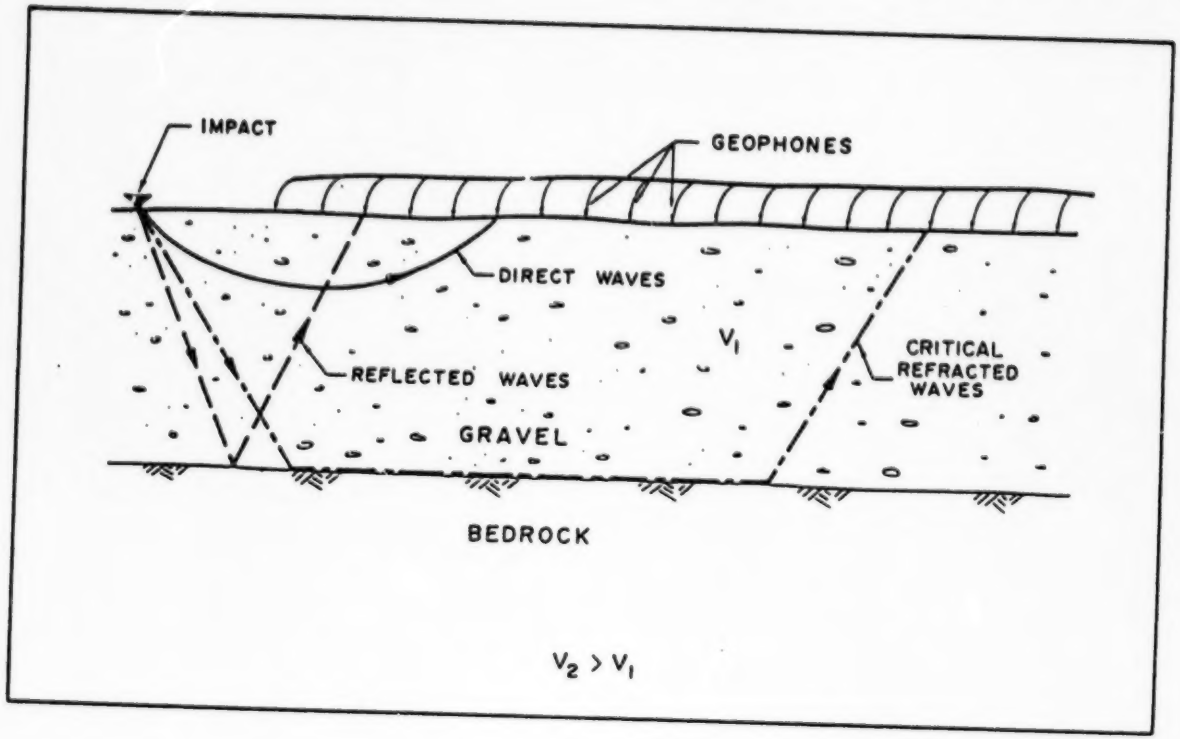


FIGURE B-1 SCHEMATIC ILLUSTRATION OF PATHS OF DIRECT, REFLECTED, AND CRITICAL REFRACTED WAVES FROM A SURFACE SOURCE TO SURFACE GEOPHONES

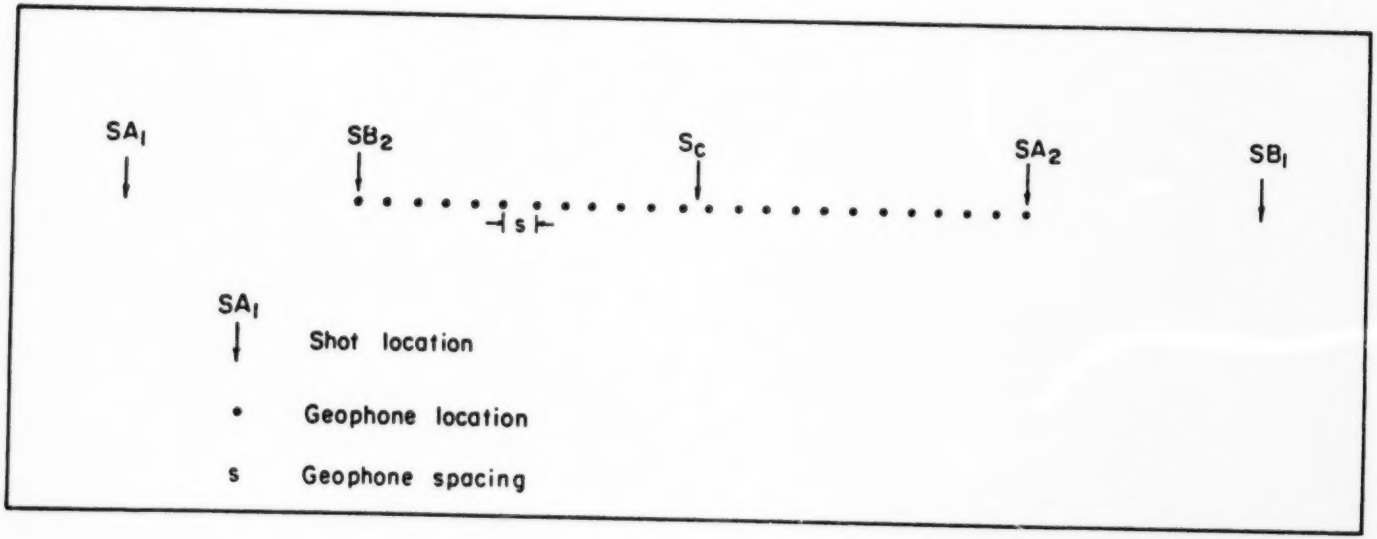


FIGURE B-2 TYPICAL LAY-OUT OF SHOTS AND GEOPHONES FOR SEISMIC REFRACTION PROSPECTING

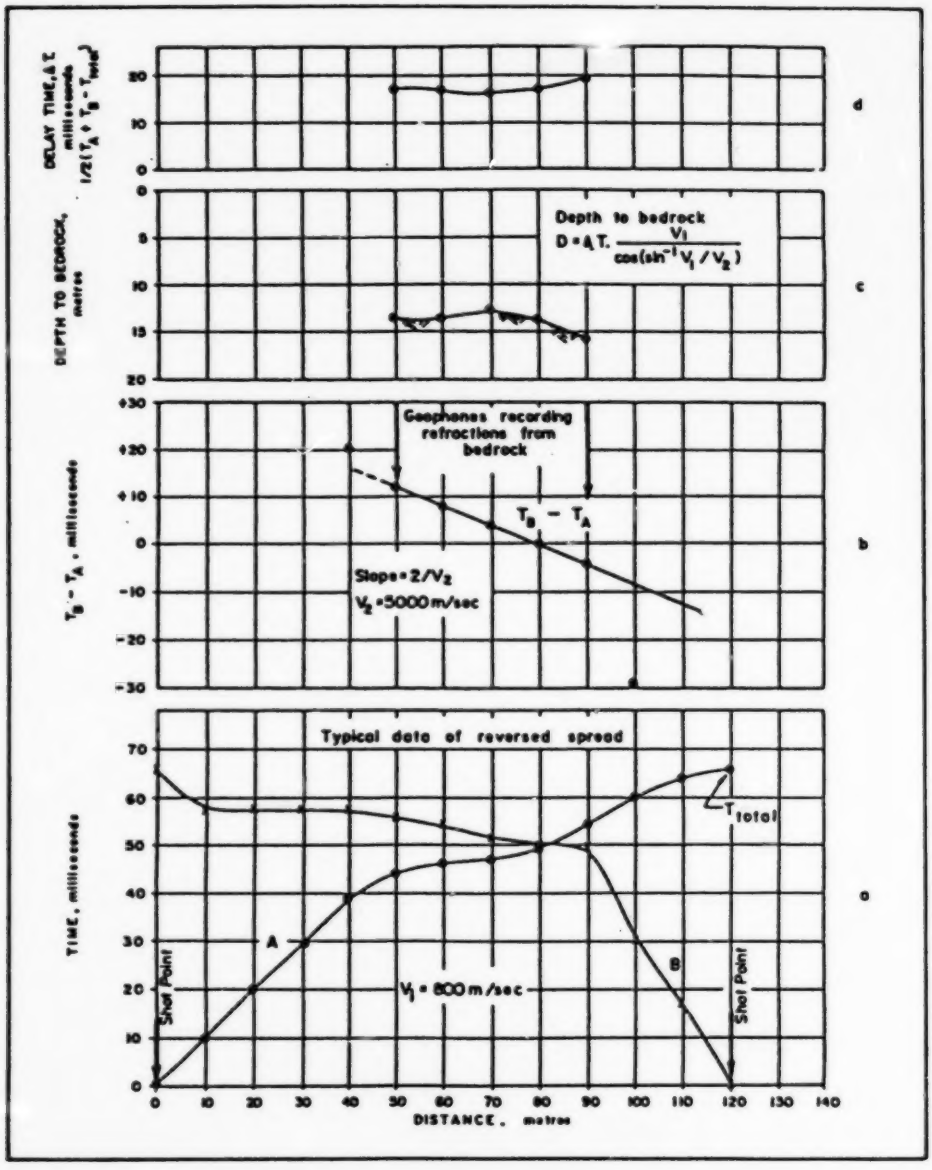


FIGURE B-3 TYPICAL EXAMPLE OF MEASURED TRAVEL TIMES AND PROCEDURES OF DATA PROCESSING OF SEISMIC REFRACTION SURVEYS FOR A TWO-LAYER CASE

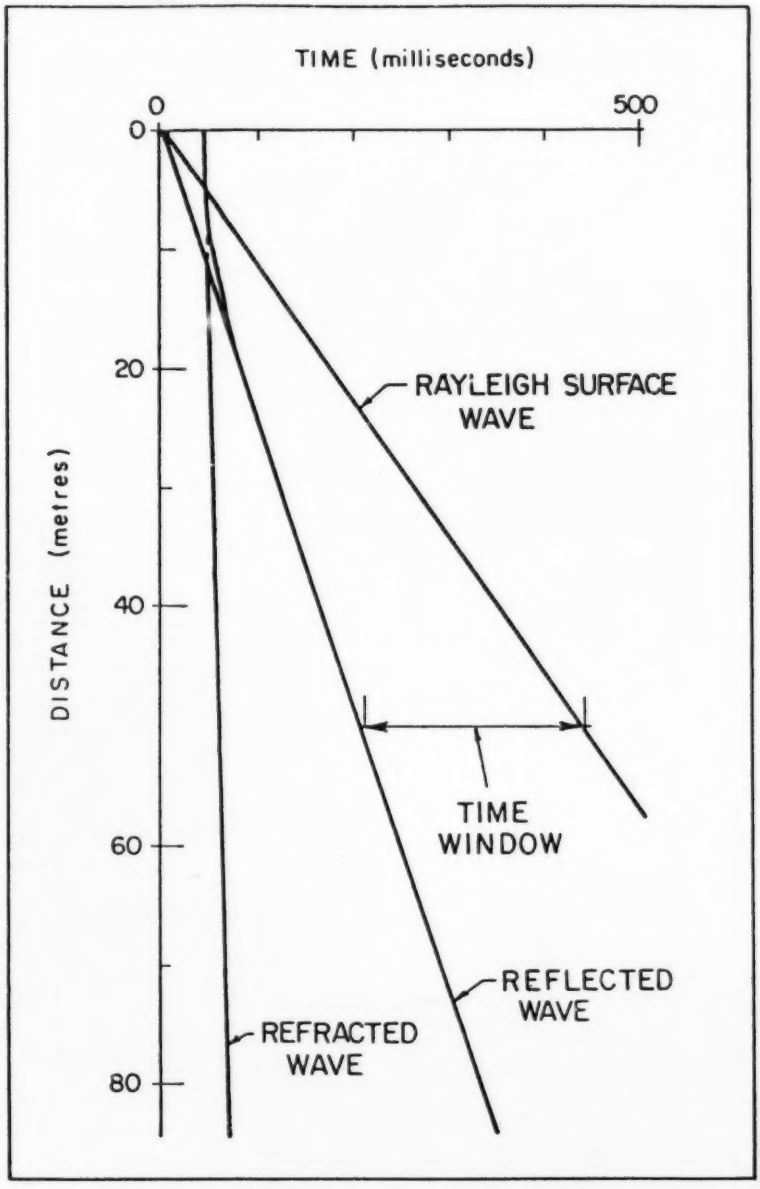


FIGURE B-4 TYPICAL TRAVEL TIME VS DISTANCE RELATION FOR DIFFERENT WAVES

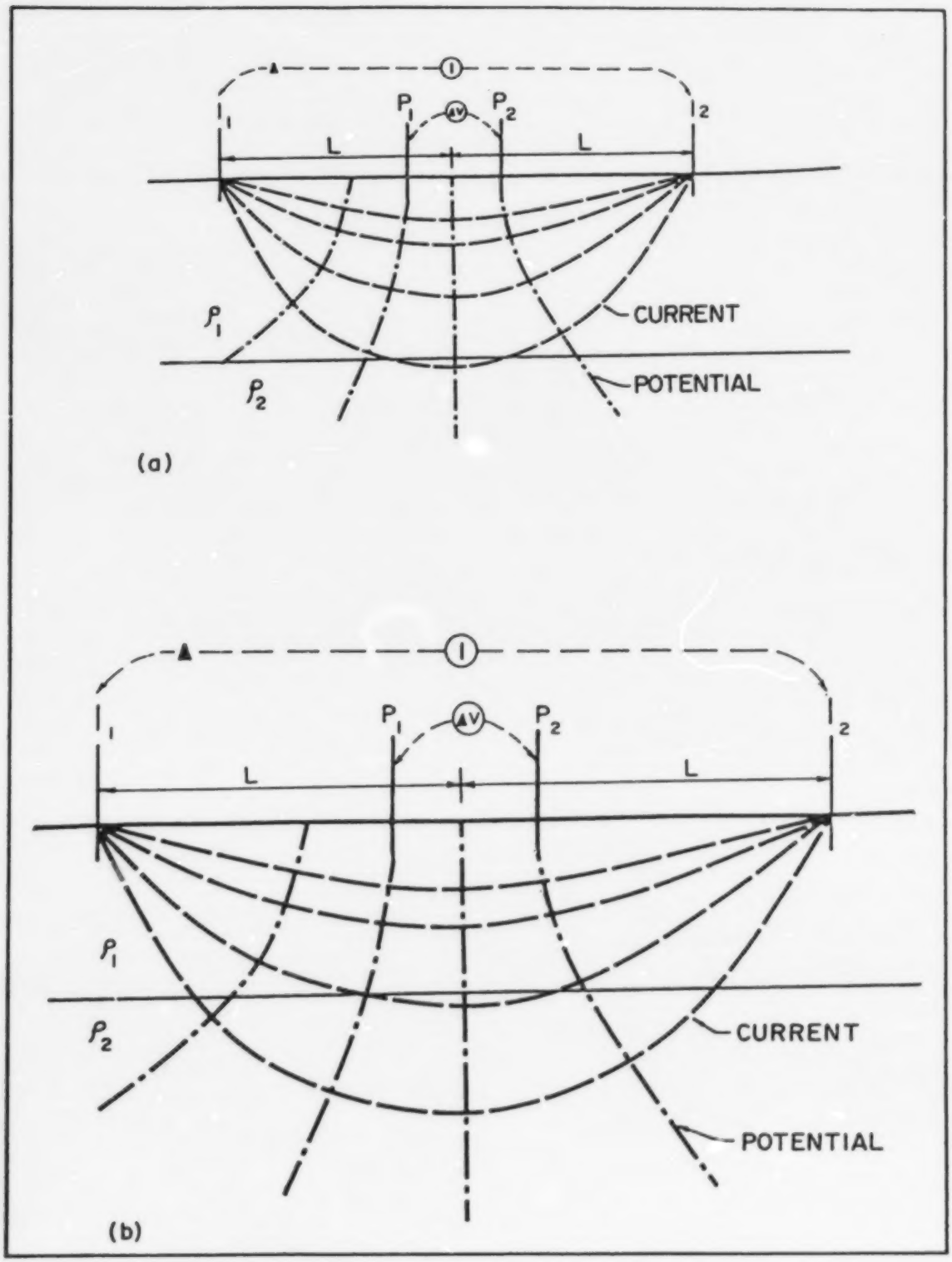


FIGURE B-5 SCHEMATIC ILLUSTRATION OF CURRENT FLOW AND POTENTIAL LINES IN A SCHLUMBERGER ARRAY. CURRENT IS DRIVEN INTO GROUND BETWEEN I_1 AND I_2, AND POTENTIAL IS MEASURED BETWEEN P_1 AND P_2. AT SMALL L-SPACINGS (a) CURRENTS FLOW MAINLY IN FIRST LAYER; WITH INCREASING L-SPACING (b), PART OF CURRENTS FLOW IN SECOND LAYER.

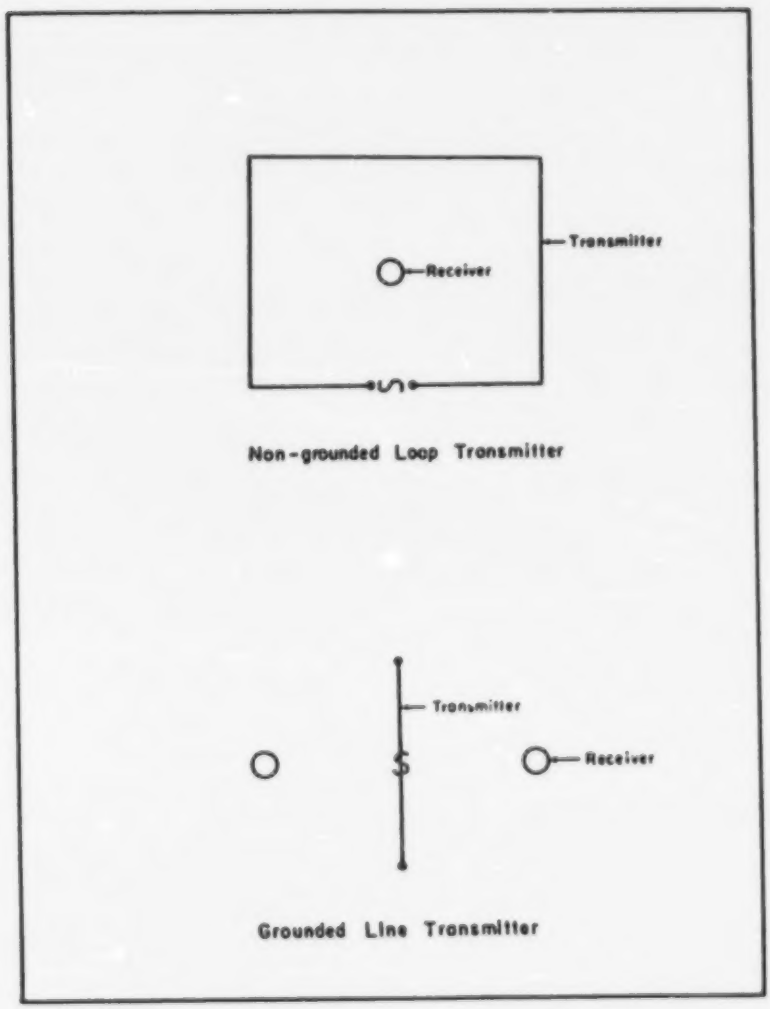


FIGURE B-6 SCHEMATIC ILLUSTRATION OF TRANSMITTER-RECEIVER ARRAYS USED IN TRANSIENT ELECTROMAGNETIC SOUNDING

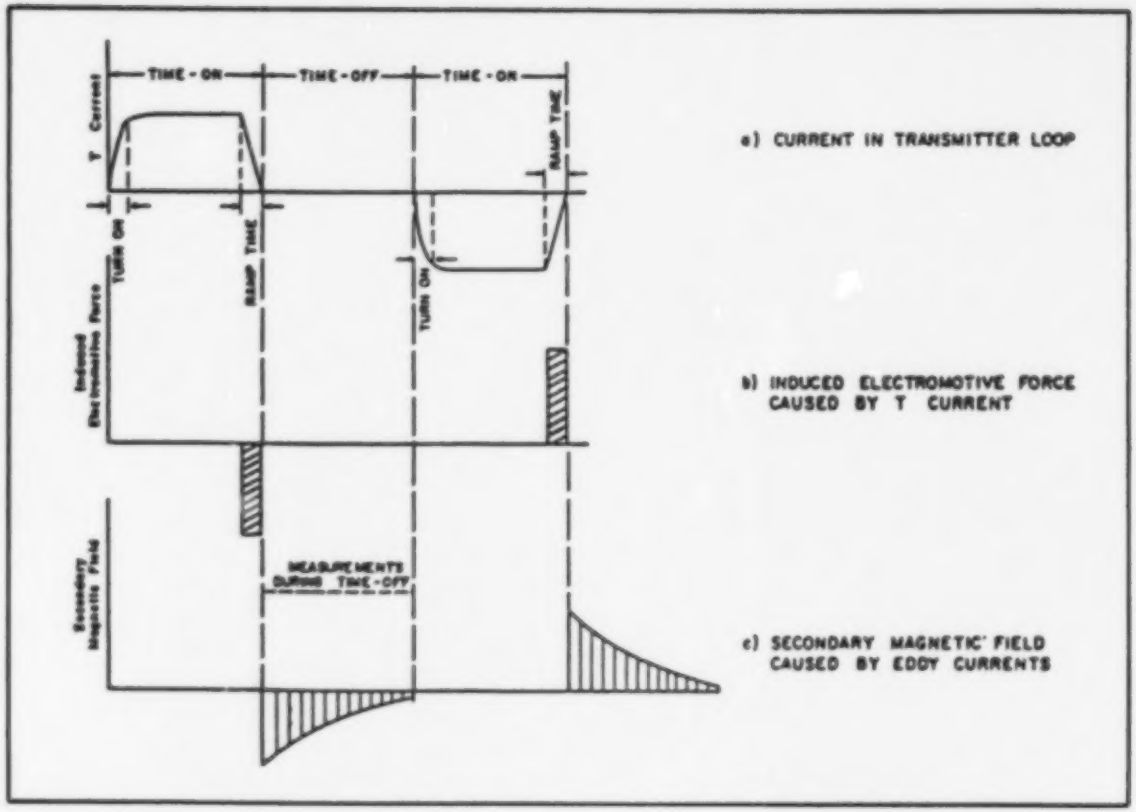


FIGURE B-7 SYSTEM WAVE FORMS USED IN TRANSIENT ELECTROMAGNETIC SOUNDINGS

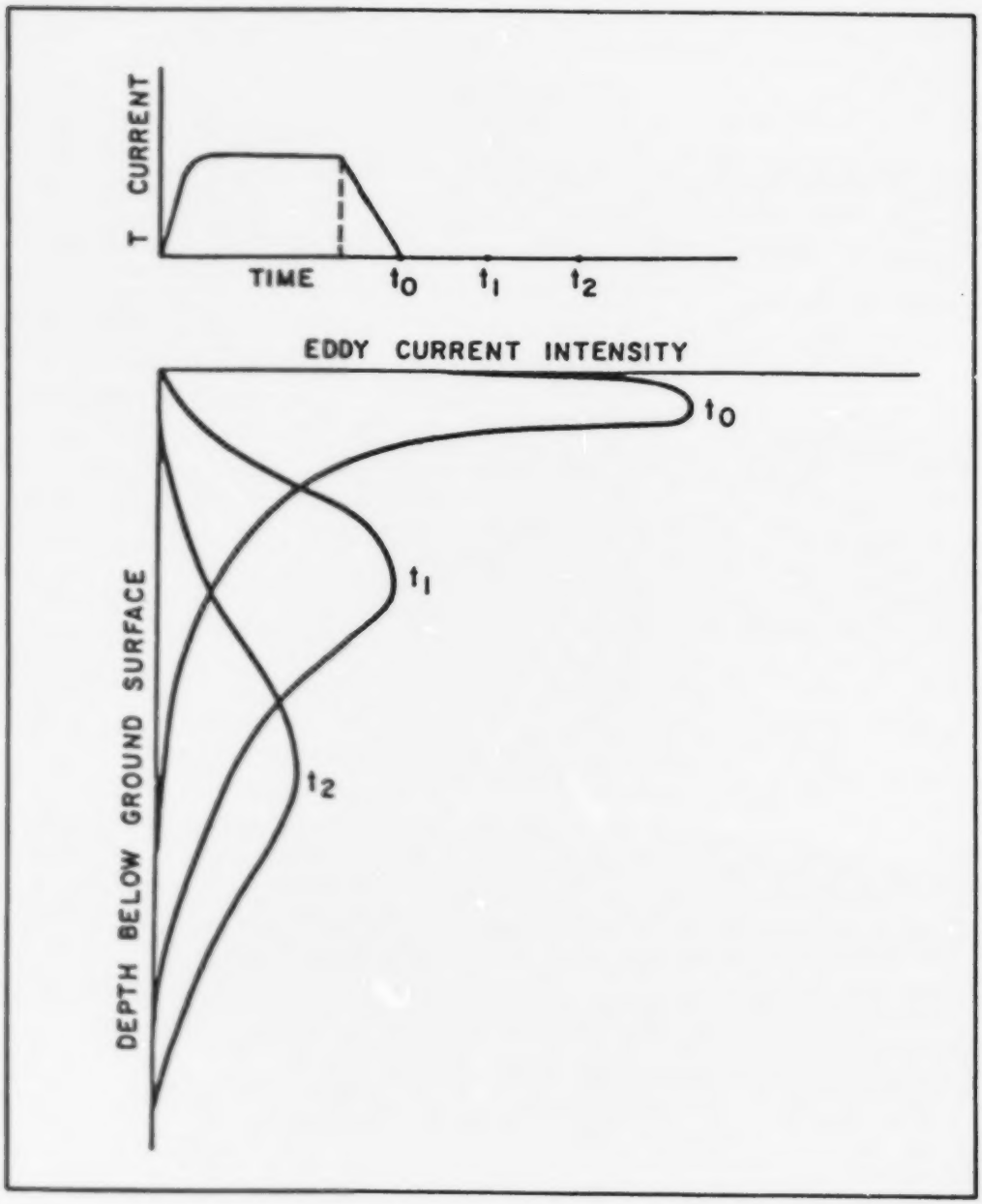


FIGURE B-8 THE BEHAVIOR OF GROUND CURRENTS AS A FUNCTION OF DEPTH AT DIFFERENT TIMES AFTER TURN-OFF

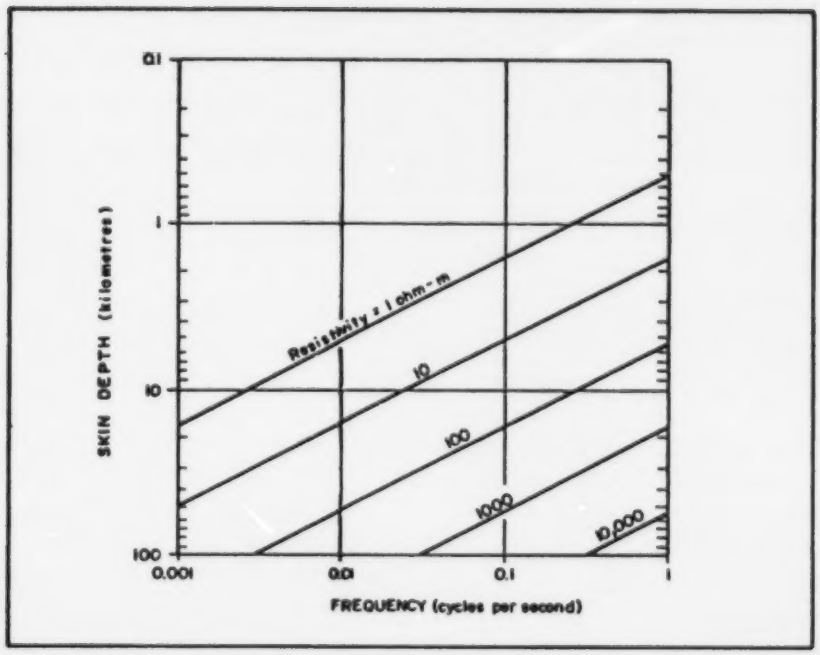


FIGURE B-9 RELATION BETWEEN SKIN DEPTH AND FREQUENCY FOR SEVERAL GROUND RESISTIVITIES

APPENDIX C

LIST OF INSTITUTIONS AND ORGANIZATIONS WITH AN INTEREST IN GEOPHYSICS APPLIED TO OIL SANDS SURFACE MINING

LIST OF INSTITUTIONS AND ORGANIZATIONS WITH AN INTEREST IN GEOPHYSICS APPLIED TO OIL SANDS SURFACE MINING

Alberta Energy Company Ltd., Calgary
Alberta Oil Sands Technology and Research Authority, Edmonton
Alberta Research Council, Oil Sands Research Department, Edmonton
Amerada Minerals Corporation of Canada, Calgary
AMOCO Canada Petroleum Company Ltd., Calgary
Applied Geomechanics Inc., Santa Cruz, California
BP Exploration Canada Ltd., Calgary
BPB Instruments (Canada) Limited, Calgary
Bechtel Canada Ltd., Calgary
Canadian Occidental Petroleum Ltd., Calgary
Can-Amera Export Refining Co. Ltd.
Canstar Oil Sands Ltd., Calgary
Canterra Energy Ltd., Calgary
Caulfield Engineering, Nisku
Century Geophysical Corporation of Canada, Calgary
Chevron Canada Ltd., Calgary
Cities Services Co., Oil Sands Technology, Tulsa, Oklahoma
Dome Petroleum Ltd., Calgary
Dresser Petroleum Engineering Services, Dresser Atlas, Houston, Texas
Energy, Mines and Resources Ltd., Calgary
Energy Resources Conservation Board, Calgary
Esso Resources Canada Ltd., Oil Sands Group, Calgary
Fluor Canada Ltd., Calgary
Geo-Physi-Con Co. Ltd., Calgary
Gulf Canada Resources Inc., Calgary
Hardy Associates (1978) Ltd., Calgary
Lawrence Livermore Laboratories, Lawrence, California
Mobil Oil Canada Ltd., Calgary
Montreal Engineering Ltd., Calgary

Norcen Energy Resources Ltd., Calgary
Pan Canadian Petroleum Ltd., Calgary
Petro-Canada Inc., Calgary
Pulsonic Geophysical Ltd., Calgary
Roke Oil Enterprises Ltd., Calgary
Schlumberger of Canada, Calgary
Shell Canada Resources Ltd., Calgary
Southwest Research Institute, San Antonio, Texas
Suncor Inc., Resources Group, Oil Sands Division, Ft. McMurray
Syncrude Canada Ltd., Ft. McMurray and Edmonton
Tenneco Energy Ltd., Houston, Texas
Terracon Geotechnique Ltd., Leduc
Terra-Tek Research, Salt Lake City, Utah
Texaco Canada Resources Ltd., Calgary
University of Alberta, Edmonton
University of Calgary, Calgary
University of Wyoming, Research Corporation, Laramie, Wyoming

Selected organizations/individuals who are known to be currently active in the research, development or application of geophysics to oil sands and/or geotechnical definitions are listed below. This list is based on personal knowledge of the authors and may not be complete.

AECL and GSC

Seismic tubewave applications for fracture definition in crystalline rock.

Caulfield Engineering

Reflection seismic feasibility studies.

Cities Services Co.

Three dimensional spatial distribution of oil sands strata using EM imaging techniques.

Geo-Physi-Con Co. Ltd.

Seismic and electrical applications for oil sand exploration.

Justice, J., University of Calgary

Vertical Seismic Profiling (VSP) tests for in-situ oil sands development.

Lawton, D., University of Calgary

Reflection seismic feasibility studies for shallow exploration.

Mwenifubo, J., Geological Survey of Canada

Borehole geophysics applied to tills for groundwater and geotechnical purposes.

TransAlta et al

Borehole geophysics research and development program for geotechnical and hydrogeological applications to coal and oil sands.

TransAlta et al, Surface Geophysics J.V.

Surface geophysics applications to coal mining for geotechnical, geological and hydrogeological definitions.

West, Gordon, University of Toronto

Tomography and vertical borehole profiling.